AMERICAN JOURNAL OF ALTERNATIVE AGRICULTURE

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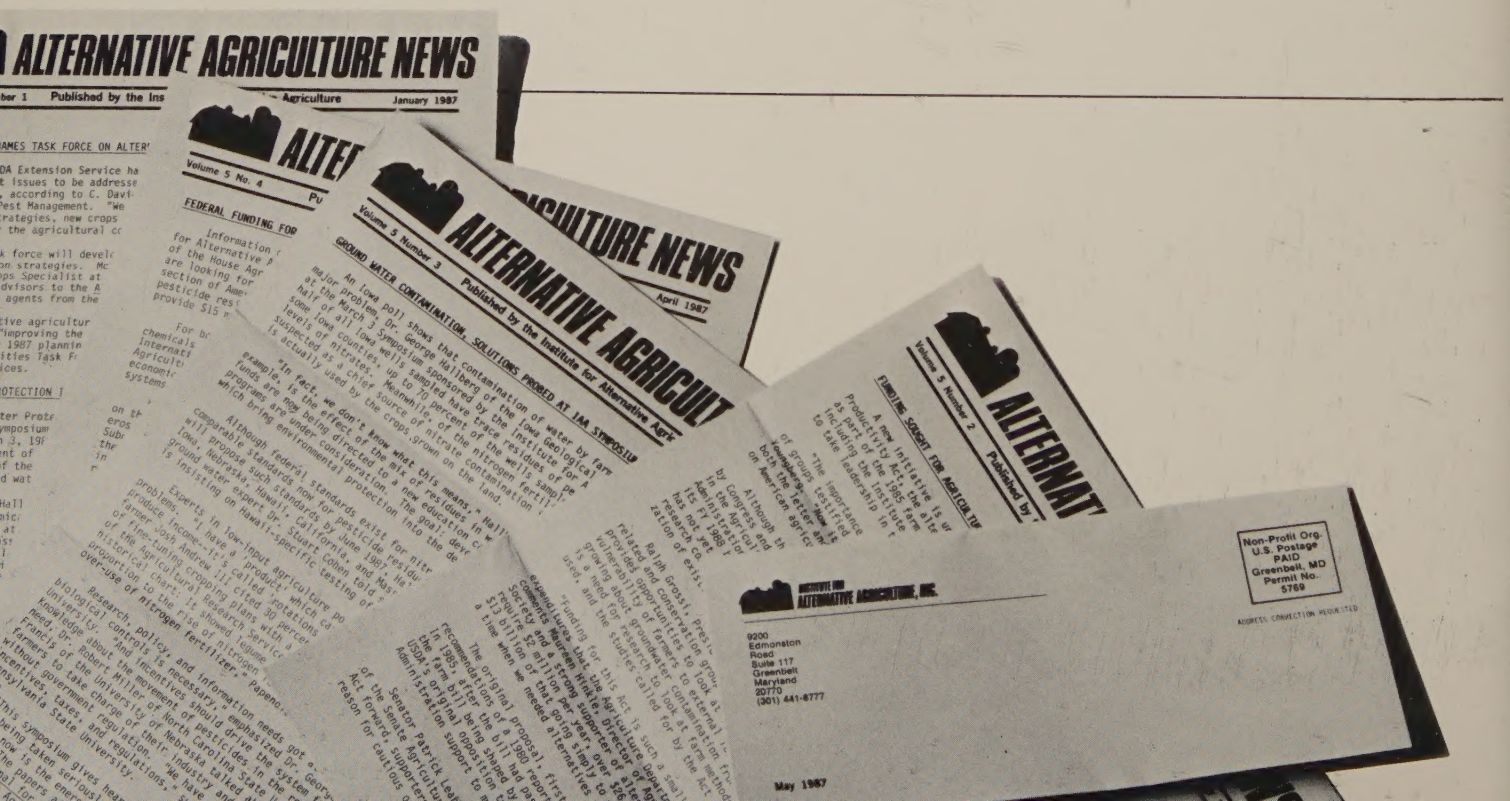

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Institute Information

The Institute for Alternative Agriculture is a nonprofit, tax-exempt research and education organization established in 1983 to encourage and facilitate the adoption of low-cost, resource-conserving and environmentally-sound farming methods. It works closely with producer groups, public research and education institutions, and government agencies in promoting a sustainable agriculture system.

Its programs include providing a national information clearinghouse, serving as a voice for sustainable agriculture in Washington, and developing and implementing research and educational outreach programs. It holds an annual scientific symposium and publishes a monthly newsletter.

The Institute is governed by a grass roots Board of Directors, which includes several commercial-scale organic farmers, and maintains a small professional staff. It is supported by memberships and donations and grants from foundations, corporations, and individuals.

Cover Photo

The cover picture shows a seven spotted lady bird beetle feeding on a pea aphid. This beetle was imported from Europe and has become established in America where it helps control aphids that attack alfalfa, other legumes, and fruit trees. Photo provided by the Agricultural Research Service, USDA.

Biologically based methods of pest control: Contributions to a sustainable agriculture

Concern continues to rise over the adverse effects of the excessive use of chemically based agricultural pesticides, including herbicides, insecticides, nematicides, and fungicides. Important members of the U.S. agricultural scientific, producer, and policy communities have added their voices to those in the environmental, consumer, and public health arenas in pointing to the need for more benign and cost effective methods and systems of pest management and control. Indeed, the urgent need to further enhance the efficacy and use of such varied, yet interrelated, approaches to pest control as pathogens, predators, and parasites (traditional biological control), and such biologically based techniques as host plant resistance, natural plant products, semiochemicals, and autocidal methods, is now widely recognized in most agricultural circles.

It is also acknowledged, however, that in order to achieve the widescale adoption of these and other biologically based technologies much critically important research, education, and demonstration work remains. Yet, unless and until the farmers, ranchers, and horticulturists in this nation and abroad acquire greater confidence in the use of these approaches, the long-term goal of creating a truly sustainable agriculture will continue to elude us. Unfortunately, the efficacy and dependability of biologically based pest controls, especially for many of our major cash crops, has yet to be adequately demonstrated to the satisfaction of many producers and agricultural policy makers. Clearly, increased support for research and education programs on biologically based pest controls is urgently needed.

In this regard, as we look ahead to the 21st century, we find it helpful to recall a statement made in 1872 by Charles Valentine Riley, a pioneer in biological pest control: "A virgin soil, enriched by the leafy mold of ages, and a harmonizing flora and fauna...gave to the early tiller of the soil in this country a rich reward with little labor; but at present he is beset with obstacles on every hand and none but the well-informed are successful; for agriculture...today, implies knowledge -- scientific knowledge!"

Riley directed the research expedition that led to importation of the vedalia lady beetle from Australia into California in November of 1888 and to its successful use in biocontrol. He recognized the great importance for a successful agriculture in the U.S. of vigorous development and dissemination of scientific knowledge. It was in this spirit that the Institute for Alternative Agriculture organized its March, 1988, symposium on biological pest control.

Means and methods must change in U.S. agriculture in response to new economic, environmental, and structural circumstances. A static approach to agricultural science and production will not suffice to address future needs in a rapidly changing world. We seek, therefore, in these symposia to describe and make widely available through published proceedings the results of recent investigations aimed toward new and i proved methods in agriculture. Information on proceedings previous symposia is available from the Institute.

At this uniquely interdisciplinary event in March of 1988, diverse group of researchers from academia, government, a industry presented an excellent overall perspective of the cu rent status, future potential, and critical needs germane to b ological methods of pest control. All agreed that increas emphasis should be placed on such methods. It was also cle however, that continued dialogue is needed to further refi approaches to the design and implementation of research a development efforts needed to support this expansion. This ne notwithstanding, we believe these 1988 symposium present tions and the proceedings that appear here point the way towa a more environmentally sound system of agriculture in the U

The Institute's board and staff thank the Jessie Smith Noy Foundation for its financial support of this symposium a other important Institute work. We also thank the members the symposium organizing committee. They are: Pedro Barbos Jerry DeWitt, Richard Harwood, George Papavizas, a George Templeton. In addition, we gratefully acknowledge t splendid cooperation of the authors and the many anonymo reviewers of the symposium papers.

This is the first time we have included two Journal numbe in a single issue. The material greatly exceeded the Journa normal length. We felt, furthermore, that publication in t separate issues would have detracted from the sense of who ness that characterized the symposium itself.

Finally, we note that the two Commentary articles includ here were not presented at the symposium and are not part these proceedings. They are, however, highly relevant to so of the broad issues that surround the trend toward biologica based methods of pest control and, therefore, provide additio guidance as we consider future needs in moving toward a s tainable agriculture.

As noted above, symposium presenters and audience part ipants alike agreed that greater emphasis should be given the improvement and wider-scale adoption of biologically bas methods of pest control. Expanded use of these technolog and other sustainable agriculture methods could reduce depletion of our natural resources and enhance environmen quality. It is important that we join together in pursuing th goals. The needs and aspirations of both farmers and the gene public demand this of us. We solicit your enthusiastic supp in moving in this direction. To this end, we must act toget in an attitude of unity and cooperation. Let us move forwa

Garth Youngberg and Richard Ridgway, Symposium Chairs and Editors

Biological control and holistic plant-health care in agriculture

R. James Cook

Abstract. *Biological control is defined broadly as the "use of natural or modified organisms, genes, or gene products" to reduce the effects of pests and diseases. Physical control is the use of tillage, open-field burning, heat-treatment (pasteurization), and other physical methods, usually to eliminate pests or separate them from the crop. Chemical control is the use of synthetic chemical pesticides to eliminate pests or reduce their effects. The many approaches to biological control can be categorized conceptionally into 1) regulation of the pest population (the classical approach), 2) exclusionary systems of protection (a living barrier of microorganisms on the plant or animal that deters infection or pest attack), and 3) systems of self-defense (resistance and immunization). The agents of biological control include the pest- or disease-agent itself (sterile males or avirulent strains of pathogens), antagonists or natural enemies, or the plant or animal managed or manipulated (immunized) to defend itself. The methods range from 1) conserving and making maximum use of indigenous (resident) biological control through cultural practices, 2) making one-time or occasional introductions of genes or natural enemies that are more or less self-sustaining and 3) making repeated introductions of a biocontrol agent (e.g. a microbial pesticide). Biological, physical, and chemical treatments and pest controls can be integrated into holistic plant-health care also known as integrated crop and pest management. Eight principles of plant health care are offered: 1) know the production limits of the agroecosystem; 2) rotate the crops; 3) maintain soil organic matter; 4) use clean planting material; 5) plant well-adapted, pest-resistant cultivars; 6) minimize environmental and nutritional stresses; 7) maximize the effects of beneficial organisms; and 8) protect with pesticides as necessary.*

Key words: plant diseases, fungi, bacteria, viruses, nematodes, plant breeding, cultural practices, tillage, planting date, non-pathogens, biocontrol agents

Introduction

In considering the contributions of biological pest control to a sustainable agriculture, it may be useful first to examine briefly some of the advantages and disadvantages of each of the major methods by which pests can be controlled. The major methods of pest control can be grouped into three categories of 1) physical control, 2) chemical control, and 3) biological control. These broad categories, in turn, can be combined into integrated pest management (IPM), integrated crop and pest management (ICPM), or, as will be used in this article, holistic plant-health care or simply plant-health care. The equivalent for livestock is integrated livestock management or animal health care.

Physical control includes tillage to control weeds, open-field burning to control pests (Hardison, 1976), solar-heating the soil beneath clear plastic tarp (Katan, 1981), elimination of pathogens from milk or rooting media by mild heat-treatment (Baker, 1962), the production of pathogen-free plants from tissue culture started with clean meristems or shoot tips (Holings, 1965), and the physical separation of crop from a potential pest attack by choice of planting date. The production of pathogen-free plants from tissue culture is nonpolluting and, along with indexing of seeds, is the best or only acceptable method to eliminate some viral and bacterial pathogens so that the planting material can be certified as pathogen-free (Holings, 1965). On the other hand, tillage is energy-expensive (Phillips et al., 1980) and contributes to soil erosion; the trend in the United States is therefore toward less tillage to conserve energy, reduce soil erosion, and make U.S. agriculture more sustainable. Open-field burning contributes to air pollution and may, over the long term, have a negative effect on the organic matter content of soil; the tendency is therefore toward reduced use of burning, and legislation has been introduced in some states to regulate or even ban open-field burning. Solar-heating the soil involves the capture of incoming solar radiation beneath clear plastic sheeting placed on the soil surface. It is a safe method by which plant-parasitic nematodes, soilborne fungal pathogens, soil-inhabiting insect pests, and some weed seeds can be eliminated by heat treatment of soil in gardens, vegetable fields, and orchards (Ashworth et al., 1982), but is usually not economical except for high-value crops and in areas of abundant sunshine.

Chemical control is used in this report to mean control of pests with chemical pesticides. The problems of chemical pesticides have been reviewed amply and need not be restated here. While some pesticides must be abandoned because of their unacceptable nontarget effect, there will always be a need in agriculture for safe and selective chemicals to limit

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the effects of pests. More significantly, it is becoming increasingly more difficult and expensive to find new kinds of synthetic chemical pesticides. The chemical pesticide industry has therefore been described as a "maturing industry."

Biological control is the control of one organism by another (Beirner, 1967). This control may be expressed as either a lower population of the pest (DeBach, 1964) or as a restriction or prevention of the severity or incidence of pest damage without regard to the pest population (Cook and Baker, 1983). Biological control depends on knowledge of biological interactions at the ecosystem, organismal, cellular, and molecular levels and often is more complicated to manage compared with physical and chemical methods. Biological control is also likely to be less spectacular than most physical or chemical controls but is usually also more stable and longer lasting (Baker and Cook, 1974). In spite of biological controls having been used in agriculture for centuries, as an industry biological control is still in its infancy.

Biological control is now being considered for an increasing number of crops and managed ecosystems as the primary method of pest control. One reason for its growing popularity is its record of safety during the past 100 years considered as the era of modern biological control (Waage and Greathead, 1988). No microorganism or beneficial insect deliberately introduced or manipulated for biological control purposes has, itself, become a pest so far as can be determined, and there is no evidence so far of measurable or even negligible negative effects of biocontrol agents on the environment (in Cook, Chairman; 1987). Another reason for considering biological control over other methods is untapped potential; biological control is underused, underexploited, underestimated and often untried and therefore unproven. The new tools of recombinant DNA technology, mathematical modeling, and computer technology combined with a continuation of the more classical approaches such as importation and release of natural enemies and improved germplasm, breeding, and field testing should quickly move biocontrol research and technology into a new era.

Biological control describes the normal state of affairs in natural undisturbed ecosystems, where populations of organisms exist in a dynamic equilibrium and species or individuals unable to compete or to find an ecological niche are replaced by those that can. With sufficient knowledge, it becomes possible to manipulate this equilibrium so as to favor some organisms more than others. Thus begins agriculture, silviculture, gardening, and other similar activities that favor a few desirable plant or animal species, or subsets of species (cultivars, breeds, strains), that otherwise could not succeed and might even become extinct.

This report is focused on biological control of pests and diseases of plants important in farmland, orchards, and other agroecosystems. Many of the examples discussed involve the control of diseases of wheat (Cook, 1986c), but the concepts presented are just as applicable to pest and disease control on other crops and in other managed ecosystems, including urban and recreational areas.

This report also introduces some principles of holistic plant-health care, which involves extensive use of biological control integrated with physical and chemical treatments and pest controls as appropriate and compatible with the goals of making agriculture more sustainable.

Biological control as a concept

Biological control was discovered by trial and error and then practiced in agriculture long before the term itself came into use (Baker and Cook, 1974). One example is the ancient practice of not growing the same crop species in the same field more frequently than every second or third year or even longer. Such crop rotation allows time for the pest or pathogen population in soil to decrease below some economic threshold because of the predatory, competitive, and other antagonistic effects imposed by the associated microflora and fauna. In other words, crop rotation allows time for the natural soil microbiota to sanitize the soil, especially with regard to the more specialized plant parasites and insect pests that are highly dependent on the host crop to maintain their populatio

The era of modern biological contro involving the deliberate transfer and i troduction of natural enemies of inse pests, was launched 100 years ago wi the highly successful introduction of t vadalia beetle from Australia to Ca fornia in 1888 to control the cotton cushion scale of citrus. In 1914, the Ge man plant pathologist C. F. von Tubu wrote a somewhat speculative article e titled "Biologische Bekampfung v Pilzkrankheiten der Pflanzen." This apparently the first reference in the sc entific literature to the term "Biol gische Bekampfung" or "biologic control" (Baker, 1987). In 1916, L. Howard referred to control of the co tony-cushion scale insect by the vadal beetle as a "biological method" and 1919, H. S. Smith called it biologic control (Baker and Cook, 1974).

About 80 years ago, a gene for r sistance in wheat to wheat stem ru caused by *Puccinia graminis* f. sp. *triti* was successfully transferred for the fir time by crossing a rust-resistant with rust-susceptible wheat plant (Biffe 1906). Thus began the practice of intr ducing genes for resistance to pests, fir by conventional methods and now e panded to include genetic engineering b use of recombinant DNA technolog Lupton (1984) gave emphasis to this a proach in his presidential address to t Association of Applied Biologists Great Britain, entitled, "Biological Co trol: The Plant Breeder's Objective Moreover, the boundaries that once e isted between these two approaches biological control--transfer of whole o ganisms and transfer of genes--are b ginning to disappear because of the too of recombinant DNA technology. F example, a gene for production of endotoxin by a strain of *Bacillus thuri giensis*, lethal to certain insect pests crops, has now been transferred by r combinant DNA technology to tobac and tomato and shown to function these plants as genes for resistance the toxin-sensitive insect pests of the plants (Vaeck et al., 1987).

It is commonly argued that biologic control as a concept should exclude ho plant resistance to pests and diseas

achieved by introduction of genes through plant breeding (R. Baker, 1985). Such a definition puts this science into the awkward position that the use of a plant pathogen with certain genes for virulence to maintain a population of susceptible weed plants at or below some economic threshold would qualify as biological control, but the converse, the maintenance of a pathogen population at or below some economic threshold by deployment of certain genes for resistance in the crop plants, would not qualify as biological control. As another incongruity, the *bt* gene for production of the insect toxin expressed in the insect pathogen *Bacillus thuringiensis* would qualify as biological control but the same gene expressed in plants, as a gene for resistance to insect pests, would not qualify as an example of biological control. Such a narrow definition is artificial and scientifically indefensible. Perhaps Lupton (1984) has stated it best: "accelerating or diverting evolutionary processes in order to obtain genotypes adapted to [man's] needs are a most important example of the application of biological control to agricultural and horticultural crops."

DeBach (1964) defined biological control as "the action of parasites, predators, or pathogens in maintaining another organism's population density at a lower average than would occur in their absence." This definition covers some highly successful biological controls of insect pests with natural enemies, but it does not accommodate some other highly successful controls accepted in other disciplines as examples of biological control. For example, citrus tristeza virus is controlled in Brazil by inoculating the citrus trees with a mild virus, which then protects the trees against the more severe strains (Costa and Muller, 1980). "Cross protection" was first shown by H. H. McKinney in 1929 to have potential for biological control of plant viruses. Plant pathologists refer to cross protection for control of plant viruses as biological control.

The many biological controls that fall outside the narrow definition have been variously labeled as "biological methods of control," "biological forms of control," and "biological pest suppression" (Jones and Solomon, 1974; Lundholm and Stackerud, 1980). All of these terms, like H. O. Howard's original "biological method," mean simply "biological control."

I propose that scientists adopt a definition of biological control that can encompass what scientists worldwide have long called biological control. Such a broad definition is given in the recent "Report of the Research Briefing Panel on Biological Control in Managed Ecosystems" (in Cook, Chairman; 1987) as: "the use of natural or modified organisms, genes, or gene products to reduce the effects of undesirable organisms (pests), and to favor desirable organisms such as crops, trees, animals, and beneficial insects and microorganisms." A major achievement of this report is that it provides a scientific framework that accommodates all approaches to biological control for all categories of pest-agents. This scientific framework breaks down into strategies, agents, and methods discussed below.

Strategies of biological control

The seemingly unlimited array of different approaches to biological control can be categorized quite simply into three strategies (in Cook, Chairman; 1987): 1) Regulation of the pest population; 2) Exclusionary systems of protection; and 3) Systems of self-defense (Figure 1).

Regulation of the pest population

This approach to biological control uses biological control agents to regulate the pest population at or below an acceptable threshold of pest population and/or plant injury. Some 10-15 weed species are now controlled partly or completely by insects or plant pathogens released because of their ability to feed on or parasitize these weeds. The population of soilborne plant pathogens can be regulated biologically by taking advantage of resident antagonists through a cultural practice such as crop rotation. Regulation of the pest population is the only acceptable strategy for many if not most insect pests, plant parasitic nematodes, rodents, and weeds.

Exclusionary systems of protection

This strategy aims at the use of beneficial microorganisms as a living barrier to exclude infection or deter pest attack. The control of crown gall of ornamental shrubs (e.g. roses) and certain fruit trees is an example. Bare-root transplants are dipped into a suspension of cells of the avirulent antibiotic-producing strain K84 of *Agrobacterium radiobacter*, which then protects the roots against infection by the virulent antibiotic-sensitive *A. tumefaciens* (Kerr, 1980). An example with livestock is the use of a nonpathogenic *Lactobacillus fermentum* introduced into newborn piglets to exclude the pathogenic *Escherichia coli* from the intestinal lining and thereby protect the piglets from neonatal scours (Hill, 1985). This approach also has potential for post-harvest protection of fruits against rots caused by fungi. These fungi infect through wounds or abrasions in the skin of the fruit and traditionally have been controlled by submerging the fruit in a fungicide solution after harvest and before packing. Several such rots have now been controlled experimentally by use of nonpathogenic antifungal bacteria instead of fungicides (Wilson and Pusey, 1985).

Systems of self defense

This strategy accepts that the pest population cannot be regulated directly and that some amount of infection or pest attack will occur. However, the opportunity to use biological control still exists, namely, through the systems of self-defense in the plant itself that can limit disease severity or pest damage. These mechanisms of self-defense may be constitutive, i.e. they may be an "up and running" feature of the living plant, they may occur as a response to attempted infection or pest attack, or they may be dependent for expression on vigor and health (vitality) of the plant. Avoiding the stresses that predispose plants to disease is critical to maximizing the kinds of self defense dependent for

Biological Controls

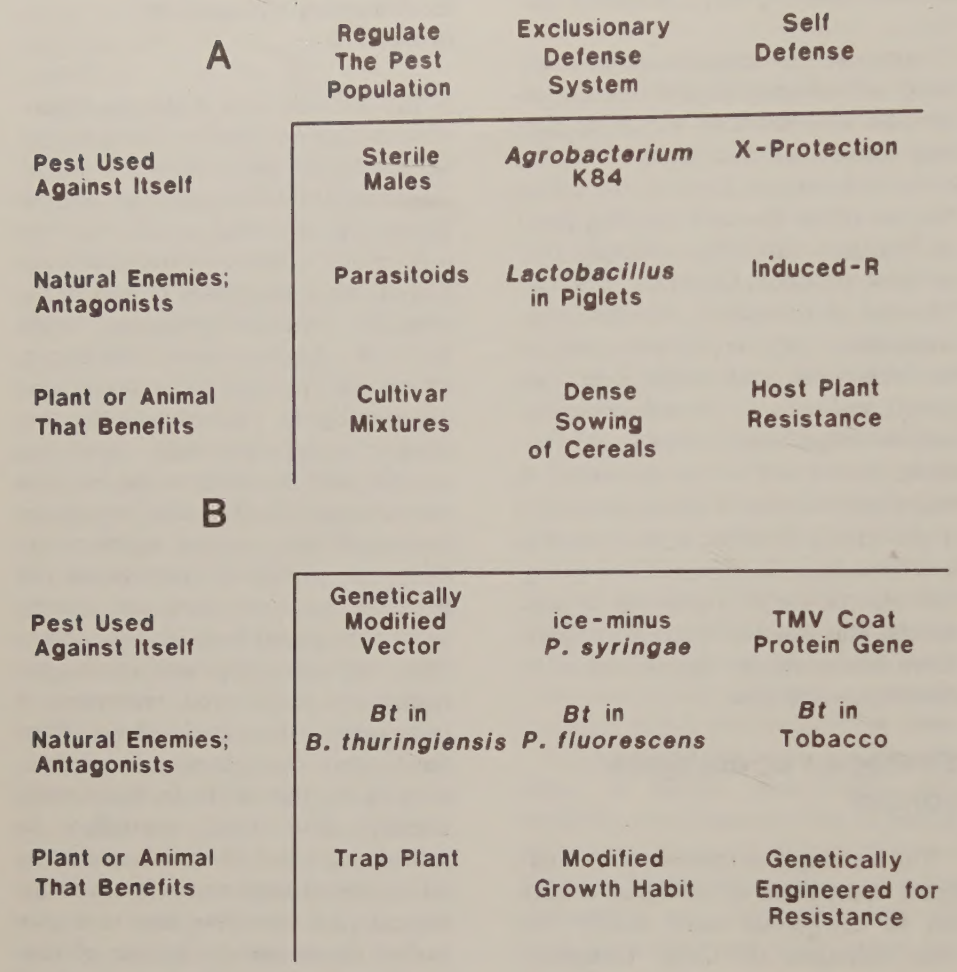

Fig. 1 A, B. Examples of biological pest control categorized according to strategy and biocontrol agent. A) Mainly traditional examples, most of which are used commercially. B) Mainly experimental and involving the use of recombinant DNA technology.

expression on vigor of the suscept, especially defense against the so-called opportunistic pathogens and weak parasites (discussed in more detail below).

Resistance to more specialized disease-agents and pests traditionally has been obtained in plants by genetic improvements, and in animals by immunization. Some plants can also be "immunized" (this term is used advisedly because the mechanism of protection in plants is very different from that in animals) against their pathogens by prior inoculation with an avirulent strain of the pathogen, or in some cases by inoculation with an organism pathogenic on another plant (Kuc, 1982). Often, these agents are pathogens of other crops and therefore are not used commercially for biological control. Nevertheless, considerable "induced resistance" or "immunization" of plants to diseases probably occurs naturally in response to the many kinds of microorganisms that make contact with plants below- or above-ground during the growing season.

Agents of biological control

The agents of biological control can include 1) the pest or disease-agent used against itself, 2) antagonists or natural enemies of the pest or disease-agent, 3) the host plant or animal managed or manipulated to defend itself (Figure 1

The pest used against itself

Examples of an insect pest use against itself include the release of steri males or the use of behavior-modifyin pheromones produced by insects to re ulate the population (strategy 1) of ce tain insect pests over wide geographi areas or within specific orchards or othe agroecosystems. A disease-agent ca also be used against itself in an exclu sionary system of defenses (strategy 2 such as the use of an ice-minus (ice⁻ strain of *Pseudomonas syringae*, applie to the foliage of frost-sensitive plants, t exclude ice-nucleation-active (INA strains of *P. syringae* (Lindow, 1983). nonpathogenic ice⁻ strain can be pr duced from a wild-type INA strain b a single deletion-mutation using th tools of recombinant DNA technolog Such strains were recently approved f field testing in California. The examp of cross protection with a mild strain a plant virus for biological control severe strains of the virus illustrates th pathogen used to initiate self-defens (strategy 3) within the otherwise ful susceptible (sensitive) plant. It is no possible to obtain significant control tobacco mosaic virus (TMV) in tobacc and tomato by incorporation of th TMV gene for coat-protein productio into the plant genome (Abel et al., 1986 such transgenic plants apparently a better equipped than their progenito to defend themselves against TMV. Th approach avoids the risks sometimes a sociated with deliberate inoculation plants with mild strains of plant virus (Fulton, 1986).

Antagonists and natural enemies of pests

The antagonists and natural enemi of pests include the classical biocontr agents imported, mass-reared, and r leased to control a pest population (stra egy 1). This approach, used again insect pests and weeds, is one of th major ongoing success stories in biolo ical control in the world today. Oth

success stories include the use of antagonists applied to pruning wounds to provide an exclusionary system of protection (strategy 2) against pathogens (Corke, 1978; Rishbeth, 1979). One emerging technology is the use of plant-associated microorganisms such as root-colonizing bacteria (rhizobacteria) to protect germinating seeds and roots against soilborne pathogens (Cook et al., 1987a; Schroth and Hancock, 1982). The rhizobacteria can be introduced on the seeds, seedpieces, or cuttings and are selected for their ability both to colonize the germinating seeds and roots and to inhibit the target pathogens (Cook and Baker, 1983). As a third approach, the ability of plants to defend themselves (strategy 3) can sometimes be enhanced or the time required for a resistance-type response in the plant can be shortened by prior inoculation of the plant with an agent totally unrelated to the pathogen (Kuć, 1982; see previous section).

Plants as agents of biological control

Plants can also be used as agents of biological control in any one of the three strategies outlined above. The plant can be used as a trap to regulate the population of plant parasitic nematodes (strategy 1). An example is the growing of *Crotalaria spectabilis* as a cover crop in peach orchards to reduce the population of root-knot nematodes (McBeth and Taylor, 1944). The female larvae responsible for root-knots in fully-susceptible host plants were shown to penetrate the roots of *C. spectabilis*, but because giant cells essential to the parasitic relationship did not form, the immobilized females did not lay eggs. An example of an exclusionary system of defense (strategy 2), using the plant, is to increase the seeding rate or narrow the row spacing of the crop so as to exclude weeds. The various narrow row-spacings selected for small grains, for example, are mainly for weed control by exploiting the competitive ability of the crop. Finally, plants can be managed culturally or manipulated genetically so as to maximize their physiological and biochemical systems of self defense (strategy 3). This is accomplished by use of practices to minimize predisposing stresses that limit ability of the plant to defend itself, or by conventional or non-conventional breeding designed to improve the ability of the plant to defend itself.

Methods of biological control

The methods of biological control can be categorized into a logical order of 1) conserving or making maximum use of the indigenous biological controls, 2) making one-time or occasional introductions of genes or organisms that then become somewhat self maintaining, and 3) making repeated introductions of biocontrol agents in the form of products such as microbial pesticides.

Any program aimed at biological control of a specific pest or disease should begin by making maximal use of the indigenous or constitutive (background) biological controls. This may be accomplished by use of cultural practices intended to take maximal advantage of or at least not upset the beneficial biological interactions that limit the population or damaging effects of pests and diseases. Crop rotation is one such practice. Tillage is another such practice; besides providing physical control of weeds, tillage can also 1) intensify the natural biological stresses on populations of pathogens in soil, 2) accelerate the displacement of pathogens by nonpathogens in crop residue in soil, and 3) relieve predisposing stresses on the crop such as may occur in response to compact soil, poor drainage, or a pressure pan (Allmaras et al., 1988). The means to maximize or at least conserve the biological controls provided by the soil microbiota, indigenous beneficial insects, and existing resistance in plants to pests and diseases can and have been discovered mostly by trial and error but could be used with much greater success if more fundamental knowledge of these systems and of the biological interactions were available.

To the extent that the indigenous biological control is inadequate or no longer effective, one time or occasional introductions of natural or modified organisms or genes generally are considered. Many pests remain for years in a state of suppression, until some change in the farming practice upsets the balance and permits the pest to flourish. In other cases, a pest may escape its natural enemies, as when inadvertently introduced into a new environment. The intent of a one-time or occasional introduction is to reestablish a favorable balance between the crop plant and its pest, or between natural enemies and the pest, and therefore restore some semblance of the original balance or create a new state of pest suppression. Wheat-stem rust is managed in the Great Plains and Prairie Provinces of North America by strategic deployment and pyramiding of genes for resistance in the network of cultivars grown in this large area in response to the genes for virulence identified and monitored in the mixture of races of the pathogen active in the area (Roelfs, 1988). The classical approach of introducing exotic natural enemies of naturalized arthropod pests and weeds mentioned above also exemplifies this method.

As a third general method, biological control agents can be introduced repeatedly, perhaps with each sowing of the crop or perhaps several times during the growing of a crop. Herein lies the opportunity for insect pathogens such as *Bacillus thuringiensis* or baculoviruses for insect control (Payne, 1988), the use of specialized fungal pathogens of weeds such as mycoherbicides (Templeton et al., 1986), and the application of antagonists of plant pathogens to seed or other planting material (Cook and Baker, 1983) for disease control. Microbial "pesticides" offer several advantages over synthetic chemical pesticides, including no known or only limited negative effects on the environment and no known problems thus far of pests becoming resistant to the microbial agent(s). Some antibiotics, if applied in purified form as a chemical, may actually be more hazardous in the environment than some synthetic chemical pesticides. These hazards are greatly reduced when a "live delivery system" is used; the chemical is more likely to be released slowly, exactly where needed, and at much lower concentrations than

if purified and applied as single or multiple doses. Microbial biocontrol agents also tend to fill rather than create vacant biological niches and usually affect only the target pest species, and many successful antagonists use more than one mechanism to inhibit sensitive pathogens. Microbial biocontrol agents are therefore less likely than chemical pesticides to provide an opportunity for a new pest or resurgence of the original pest.

Holistic plant-health care

Holistic health has become somewhat popularized with regard to humans and animals, but is rarely considered in relation to plants. Below is an attempt to summarize some of the scientific principles that should be taken in account as approaches to holistic plant-health care (Figure 2). Most of these principles are consistent with the approaches to integrated crop and pest management (ICPM).

Know the production limits of the agroecosystem

Production limits of the agroecosystem might also be called the law of the most limiting factor in the environment. The limiting factor in the environment to yield of wheat in most areas of the world is available water. The limiting environmental factor to yield of corn could be water, growing degree-days, or possibly carbon dioxide available for photosynthesis, depending on the area. For yield of potatoes, the limiting environmental factor is thought to be total sunshine during the period of vegetative growth (van der Zaag, 1984). Crop yields can also be limited by depth of soil and soil fertility.

The management system imposed on a crop in any given year or area should take into account the most likely yield-limiting factor in the environment for that crop, year, and area. A crop managed through choice of planting date or fertilized for a yield higher than is attainable based on the most limiting environmental factor may then be subject to other stresses and thereby become more vulnerable to damage by the weak and facultative type parasites. The control in eastern Washington State of Fusarium foot rot of wheat, caused by *Fusarium culmorum*, exemplifies a biological control achieved by knowing the production limits of an agroecosystem (Cook, 1980). The agroecosystem in this case is a wheat-fallow rotation in th low-rainfall (20-40 cm annual precip tation) areas of the state. This diseas became important in the early 1960 shortly after farmers in the area bega to grow the semi-dwarf wheats heavil fertilized with nitrogen. The disease wa shown to be favored by the low, mid day plant water potentials associate with high rates of N and the resultan large leaf area available for movemen of water into the atmosphere throug transpiration (Papendick and Cook 1974). Put quite simply, growers wer fertilizing for a yield higher than coul be produced or expected with availabl water. The disease was controlled by re ducing the N to rates more in line wit the yield potential for the field.

Knowing the production-limits of th agroecosystem is also necessary as means to recognize and focus on prob lems when yields are below the attain able. Yields lower than attainable ma be sought deliberately by fertilizing o irrigating for the maximum economica yield rather than the maximum yield. I many cases, however, the actual yield i some fraction of the attainable or po tential as limited by the environment an paid for as inputs. This situation call for an accurate diagnosis and usuall reveals the action of one or more pest or diseases at work in the field.

Growth, phenology, and productivit models are becoming available for mos major crop plants that are driven b thermal-time (Rickman et al., 1985), ac cumulated days of sunshine (van de Zaag, 1984), available water, and pre sumably other limiting factors of envi ronment if critical. More research i needed to integrate pest cycles and dis ease development into these kinds o models (Rouse, 1988) and also to predic more accurately the cycles and risks o climate and weather likely to set the pro duction limits of the agroecosystem.

Rotate the crops

Yields tend to decline with crop mon oculture or eventually they stabilize a some level significantly less than attain able if the crop is grown no more tha every third or fourth year in the sam field. This decline results from the grad

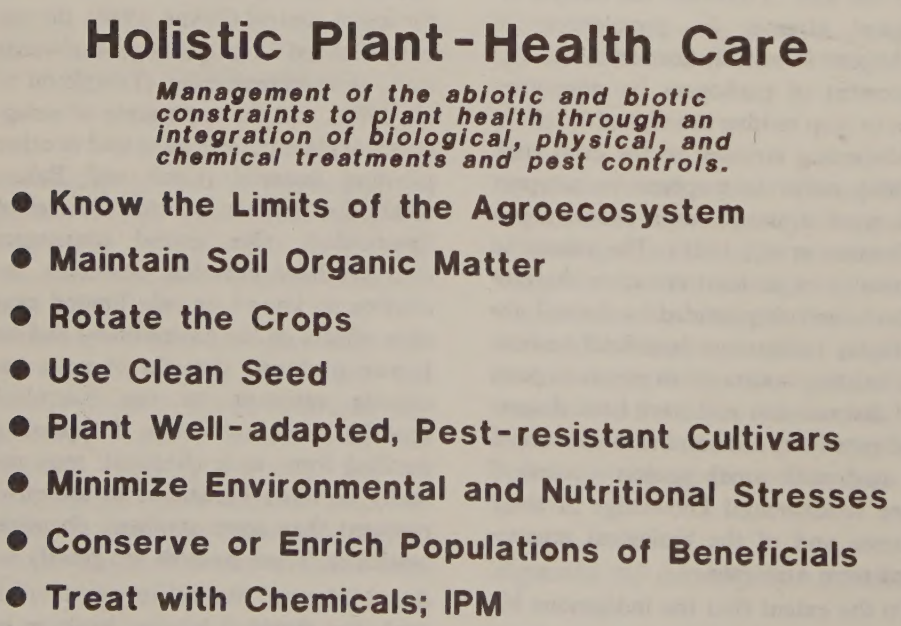
Holistic Plant-Health Care
Management of the abiotic and biotic constraints to plant health through an integration of biological, physical, and chemical treatments and pest controls.
Know the Limits of the Agroecosystem
Maintain Soil Organic Matter
Rotate the Crops
Use Clean Seed
Plant Well-adapted, Pest-resistant Cultivars
Minimize Environmental and Nutritional Stresses
Conserve or Enrich Populations of Beneficials
Treat with Chemicals; IPM

Fig. 2. Eight principles of holistic plant-health care.

ual increase in populations of plant parasitic nematodes, root-infecting fungi, and other soil-inhabiting pests and pathogens favored by that crop (Cook, 1984). Simply rotating between unrelated crop species may disrupt the cycles of these organisms. Left without access to the roots of their host, and being unable to compete for the organic substrates in soil or to attack the roots of other crops, these pests succumb quickly to the competitive effects and other stresses imposed by the associated soil microbiota active in the soil.

The growing of winter wheat in the same field in eastern Washington no more than once in three years was nearly as effective as soil fumigation with methyl bromide, chloropicrin, or 1,3-dichloropropene + chloropicrin as a means to rid the soil of the most important root pathogens (Cook et al., 1987b). One particular 3-year rotation in eastern Washington uses winter wheat followed by spring barley, spring pea (or lentil), and then back to winter wheat (Figure 3). Two successive crops of spring grains (e.g. barley or wheat) control Cephalosporium stripe caused by *C. gramineum* in winter wheat, because this disease only occurs on winter wheat or barley. However, any two consecutive crops of wheat or barley (spring- or winter-type) favor take-all caused by *Gaeumannomyces graminis* var. *tritici*. A single year to a crop other than wheat, barley, or a susceptible grass is therefore needed to control this disease, which is accomplished by preceding the winter wheat crop with a pea or lentil crop. One grower reported that "he puts more wheat in the bin" now, by cropping only one-third of his ranch to winter wheat each year (3-year rotation), than when he planted half his ranch to wheat each year (2-year rotation) (Jon Whitman, personal communication).

Some plant species have special value as rotation crops because of their active role in the sanitization of soils. The example mentioned above of *Crotalaria spectabilis* used as a trap crop to reduce the population of root knot nematode fits this category. The wheat cultivar Festiquay has shown potential in Australia as a possible trap crop for the cereal cyst nematode *Heterodera avenae* (Rovira and Simon, 1982); a field can be safely planted to a nematode-susceptible cultivar of wheat after growing Festiquay for two or three years. Riggs et al. (1980) have shown for the soybean cyst nematode *H. glycines* that rotating susceptible with resistant cultivars of soybeans can reduce the selection pressure for new races of this nematode and extend the useful life of resistant cultivars.

Some root diseases have been shown to increase in a predictable way during the early years of monoculture of the crops but then decline unexpectedly while yields recover as the monoculture is continued. Examples include common scab of potatoes caused by *Streptomyces scabies* (Weinhold et al., 1964), root rot of sugar beet in Japan caused by *Rhizoctonia solani* (Hyakumachi and Ui, 1982), Rhizoctonia damping-off of radish (Chet and Baker, 1981), and take-all of wheat caused by *Gaeumannomyces graminis* var. *tritici* (Shipton, 1977). All are either shown or thought to be examples of natural biological control by resident (indigenous) antagonists favored by the presence of the host plant, diseased roots, and/or the particular root pathogen (Cook and Baker, 1983).

In the Pacific Northwest, the soil microorganisms responsible for take-all decline have been shown to provide highly effective biological control of *G. graminis* var. *tritici* in some wheat fields (Cook and Rovira, 1976; Cook and Weller, 1987). Unfortunately, the microbiological factor responsible for take-all decline is specific for take-all (Gerlagh, 1968; Cook and Rovira, 1976). It was therefore not surprising, in a long-term experiment in central Washington, that as take-all declined to a near-negligible level by the 15th year of wheat monoculture, Rhizoctonia root rot began to increase (Figure 4). Possibly another 5-10 years will be required to generate a decline of Rhizoctonia root rot, only to open the way for a third root disease. While crop rotations present the most sustainable method to control soil-

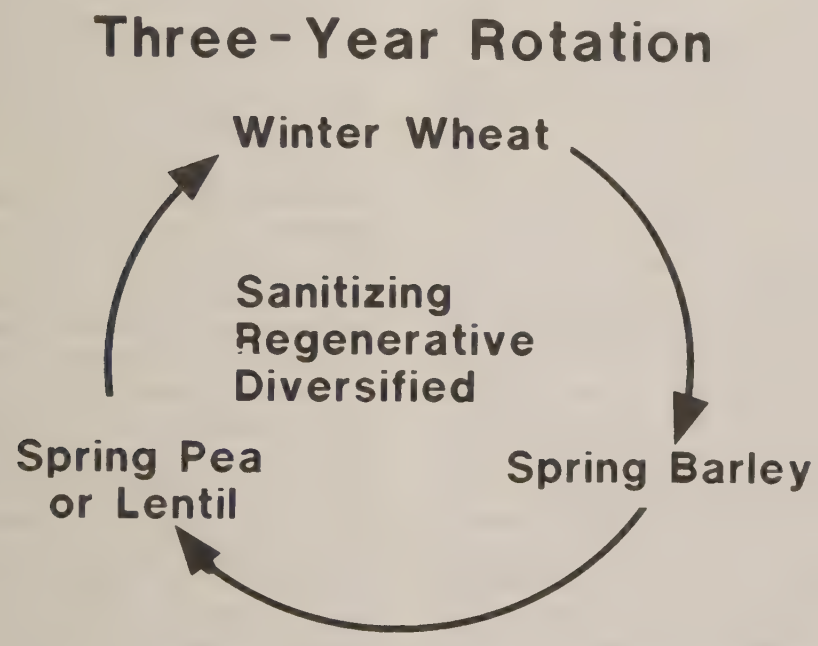

Fig. 3. An example of a sustainable agroecosystem used in eastern Washington and northern Idaho. This rotation is sanitizing because it helps rid the soil of several important soilborne pathogens and weeds. The rotation is regenerative because a) organic matter is maintained or increased by straw from the wheat and barley crops, b) water usually accumulates in the soil profile during the pea crop, for use by the winter wheat, and c) nitrogen is supplied by the pea crop. The rotation is diversified both by commodity and distribution of work between fall and spring crops.

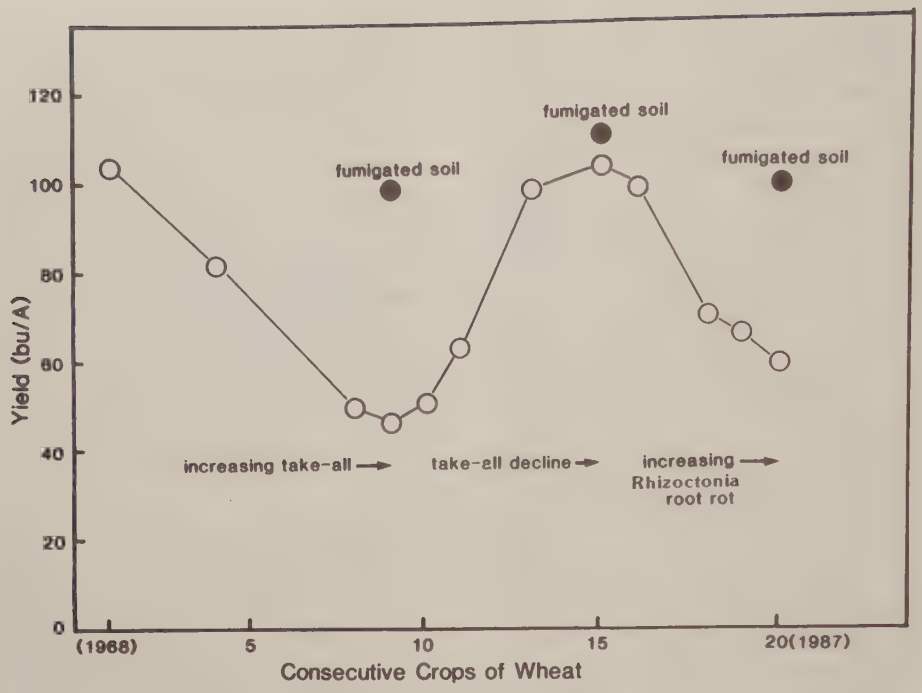

Fig. 4. Yields of winter wheat grown annually for 20 years, with tillage and irrigation, in a plot on the Washington State University Experiment Station at Lind, WA. Missing data reflect years of winter kill or agronomic problems when no yield was taken. Black circles are yields in plots made "disease-free" by soil fumigation.

inhabiting plant pathogens and pests, much can be learned about the potential for biological control of root diseases by studying monoculture-related disease-decline phenomena and other examples of pathogen-suppressive soils (Cook and Weller, 1987). Wheat rhizosphere soil taken from fields where take-all declined, for example, has yielded some interesting strains of root-colonizing bacteria (fluorescent *Pseudomonas* spp.) that now show potential for biological control of take-all when applied as living cells on the wheat seed (Weller and Cook, 1983; see below).

Maintain soil organic matter

The loss of organic matter content through years of tillage is well known to also cause a loss of soil structure. Poorly structured soils, in turn, tend to compact excessively and to drain more slowly than well-structured soils (Allmaras et al., 1988). Gas exchange and especially the availability of oxygen to roots is also restricted in such soils, which may then limit root growth directly (Russell, 1975) or predispose roots to more severe attack by root pathogens (Stolzy et al., 1965; Allmaras et al., 1988). Even a short period of restricted gas exchange in a poorly drained soil can greatly accelerate Fusarium root rot of bean and pea, apparently because the roots of these crops become physiologically much more susceptible to the *Fusarium* when denied oxygen (Miller and Burke, 1975; Smucker and Erickson, 1987). Maintaining soil organic matter content so as to maintain soil aggregates and hence good soil drainage and gas exchange in the root zone is probably the single most important factor to achieving and maintaining good root health for crops, and especially to physically limiting the effects of some soilborne plant pathogens that do not respond to biological control by crop rotation because of their broad host range.

Maintaining or elevating the soil organic matter content can also stimulate biological control of soilborne pathogens. It has long been recognized that organic mulches or amendments to t soil can lead to suppression if not ou right elimination (through germinatio lysis) of the resting propagules of ma root-infecting fungi in the soil (Papa zas and Lumsden, 1980). The exact co ponents and agents of these biologic controls are still poorly understood, b involve soil microorganisms stimulat by the amendments.

An example of biological control b maintaining soil organic matter is t use in the Mt. Tamborine rainforest Queensland, Australia, of abundant o ganic amendments to control Phyt phthora root rot of avocado caused b *P. cinnamomi* (Broadbent and Bake 1975). The goal of this highly successf method is to maintain the soil organ matter content at about 12 percent, co parable to that in the surrounding u disturbed rainforest where *P. cinnamo* is native and where many of the nati plants are susceptible yet root rot caus by this fungus is relatively rare. The b ological control achieved by this practi occurs through complex microbiologic interactions between the pathogen a resident antagonists. However, even m crobiological suppressiveness of the soils can fail if the soils become wat logged during periods of unusual heavy rainfall (Cook and Baker, 198

Plant well-adapted, pest-resistant cultivars

Only a few of the many potential pes agents of the important annual and pe ennial crops are controlled by resista cultivars. However, these few pes agents controlled are also potentiall among the most devastating and t least amenable to control by crop rot tions or soil treatments, such as the rus and powdery mildew of small grains a southern corn leaf blight of corn—d structive diseases that can quickly i crease to epidemic proportions.

An even greater number of chronic subclinical constraints to plant healt can be controlled by choosing cultiva best-adapted to the area. This can b accomplished by selecting from amo the choice of cultivars developed or least evaluated locally. Wheat cultiva with ability to avoid or tolerate pla

water stress under the semi-arid condition of east-central Washington State tend also to be the most resistant to the Fusarium foot rot (Cook, 1973). Well-adapted wheat cultivars are less likely to use up limited soil-water supplies before producing grain; they are also less likely to be injured by local winter conditions (if a winter-wheat cultivar) or to break dormancy before the last danger of frost has passed in the spring. Such cultivars tend also to be maximally resistant to weak parasites and opportunistic pathogens that depend on predisposition of the plant to cause disease (Cook and Baker, 1983; see below).

Use clean planting material

Many pest-agents, including disease agents and weed seeds, are introduced into the field or orchard on or with the planting material, or through planting operations. Potato viruses carried in the potato tubers can now be eliminated by regeneration of plants from virus-free tissue cultured from meristematic tissue (Slack, 1980). This approach is also used to produce pathogen-free banana plantlets used to establish new banana plantings in Taiwan (Hwang et al., 1984). Seedlots can be certified as pathogen-free by indexing—growing out a random sampling and checking for diseased plants as done to control lettuce mosaic virus (Grogan, 1980). The methodology used to produce pathogen-free planting material has virtually revolutionized the ornamental-plants industry (Baker and Linderman, 1979). This technology is now available to provide pathogen-free planting material for essentially all crops and to certify the planting materials as pathogen-free by highly sensitive serological methods. Such planting material sometimes costs more than the traditional material, but without good sanitation at this stage of growing a crop or starting an orchard, practices imposed at a later date may be of little value to the health and/or marketability of that crop.

Pest control by sanitation is accomplished mainly by physical and chemical methods, including sterilization of the surface of seeds or tools by heat or chemical-disinfectants, physical separation of disease-free tissue from infected plants or weed seeds from crop seeds, or physical removal of weeds or infested debris from an orchard or field. Biological control introduced on top of good sanitation can extend the period of pest and disease control started by sanitation but should not be used as a substitute for good sanitation practices (Cook and Baker, 1983).

Minimize environmental and nutritional stresses

Environmental and nutritional stresses on plants probably cannot be avoided completely during any given growing season, even with a good soil structure in the field and the use of a well-adapted cultivar. Examples of unavoidable environmental stress include chilling injury of a warm-temperature crop such as corn or soybeans, frost damage or winter injury of crops grown in the colder climates, high-temperature effects on cool-climate food crops grown in the tropics or subtropics, and water stress of crops grown in semi-arid regions. Nutritional stresses caused by clinical or subclinical deficiencies of macro- or micro-elements are also common and can vary with the growing season, stage of crop growth, and availability of nutrients released in the soil.

Some environmental stresses can kill plants outright, but more commonly they predispose plants to weak parasites and opportunistic pathogens. Deficiencies in almost any one of the macro- or micro-elements can then result in the plant becoming more susceptible to certain pests or diseases. Plants support large communities of microorganisms on or within their leaves and roots as epiphytes and endophytes. Nutritional relationships among these microorganisms range from strong and even obligate parasites (e.g. rust and powdery mildew fungi) to weak or facultative-type parasites (e.g. many *Fusarium* spp.), to strict saprophytes (e.g. most *Cladosporium* and *Stemphylium* spp.). With obligate parasites, the better the conditions for crop growth, the greater their activity and hence potential to cause damage (Baker and Cook, 1974). Biological control through use of plant genes for resistance to these parasites is the preferred method to limit their damage (see above). In contrast, the strict saprophytes associated with the living plant are essentially jockeying for position in preparation for the day when the plant is dead; they are then better positioned to take possession of the dead plant in advance of their would-be competitors. The weak parasites require only that the plant become stressed—almost dead—in order to take more thorough possession of the tissues.

Weak parasites and opportunistic pathogens should not be interpreted as unimportant pathogens. Such plants without the weak parasites would probably recover once relieved of the stress but are not likely to recover once taken over by the pathogen. Moreover, pathogens that depend on an environmental or nutritional stress of their host to cause disease often have the ability to initiate or enhance the necessary stress. This can be illustrated by three root diseases of wheat favored, respectively, by wet soil, phosphorus deficiency, and water stress. Pythium root rot of wheat, like Pythium root rot of any other crop, is favored by wet soil. This pathogen begins its attack of wheat by infecting the embryos of germinating seeds during the first 1-2 days after planting (Hering et al., 1987). Some germinating seeds are killed by the infection but most emerge as stunted seedlings. Such seedlings use less water than healthy seedlings, hence the soil is almost always wetter where Pythium root rot occurs than where plants are healthy. Pythium root rot therefore can be the cause as well as the result of the wet-soil conditions. Take-all caused by *Gaeumannomyces graminis* var. *tritici* is favored by phosphorus deficiency of wheat (Reis et al., 1982). The parasitic attack of the roots by this pathogen limits the nutrient-absorbing ability of the wheat root system; the plant with missing roots is then even more likely to become phosphorus deficient and the disease develops all the more rapidly. Fusarium root rot caused by *Fusarium culmorum* is favored by plant water-stress (Papendick and Cook, 1974; see above), which this disease also causes by developing in the crowns and tiller bases,

thereby increasing the resistance to water flow from roots to the tops of the plants.

Minimizing environmental or nutritional stresses can only be accomplished by careful crop management based on knowledge of climate and weather likely to occur in the area. Choice of planting date becomes especially critical for warm-temperature crops such as corn and soybeans, to avoid exposing these kinds of plants to chilling injury or other low-temperature stresses. Fusarium root rot or beans can be partially controlled by subsoiling, to loosen the soil and permit deeper penetration of the roots (Burke et al., 1972). The fertilization program for a crop should be developed and the precision improved through soil and/or tissue analysis for plant nutrients. It should also be pointed out, however, that since a significant number of the opportunistic pathogens favored by environment or nutritional stresses on the plant are also favored by the lack of rotation, the more frequently that crop rotation is used, the less critical the need to manage for environmental or nutritional stresses to achieve optimal plant health.

Maximize the effects of beneficial organisms

Beneficial organisms include mainly the natural enemies of insect pests discussed in other papers in this series. Beneficial organisms also include the mycorrhizal fungi associated with plant roots and responsible for more efficient uptake of phosphorus and some protection of the host roots against certain soilborne pathogens (Marx, 1972; Schenck and Kellam, 1978), and the rhizobia responsible for symbiotic nitrogen fixation on roots of leguminous plants. Some cropping systems, and especially some forms of mixed cropping, can enrich populations of organisms useful in the protection or improvement of plant health and may therefore be potentially useful (Cook and Baker, 1983). Conversely, the use of fumigants applied to soils is likely to reduce populations of nontarget mycorrhizal fungi and rhizobia, and the use of fungicides or insecticides applied to the foliage can reduce populations of beneficial epiphytes or the natural enemies of insect pests and should therefore be used only if necessary and then with care.

The large, diverse, and cosmopolitan communities of nonpathogenic microorganisms associated with plants, although probably among the first to thoroughly colonize the plants once dead, may in the meantime provide significant protection against plant disease (Blakeman and Fokkema, 1982) and insect attack (Siegel et al., 1987). The protection results from their ability to compete with pathogens on the plant surface or produce substances such as antibiotics and toxins inhibitory to pathogens or insect pests. The application of ice$^-$ strains or *Pseudomonas syringae* to protect plants against INA strains of this bacterium (Lindow, 1983), avirulent strain K84 of *Agrobacterium radiobacter* to protect roots against the crown-gall pathogen (Kerr, 1980), and antibiotic- or siderophore (natural iron-chelating compounds)-producing strains of *Pseudomonas fluorescens* to protect wheat roots against take-all (Weller and Cook, 1983) or Pythium root rot (Weller and Cook, 1987) all are examples of nonpathogenic, plant-associated microorganisms used to enhance a natural biological control by increasing the population of these microorganisms on the plant.

This kind of protection is also afforded plants against herbivorous insects, as in the case of the fungal endophyte *Sphacelia typhina* associated with tall ryegrass. The presence of this endophyte was shown to cause fescue toxicosis (summer toxicity syndrome) in cattle allowed to graze on this plant, but while removal of the endophyte eliminated the risk to cattle, it also made the plants more susceptible to certain insect pests.

Apply pesticides as necessary

Many weed species and especially insect pests and diseases of perennial (e.g. orchard) crops remain the most intractable to control by biological or physical methods and some can only be controlled economically by one or more synthetic pesticides. The system of holistic plant-health care proposed in this articl does not preclude the use of syntheti chemicals. All too often, however, chem ical controls are used instead of one o more of the first seven principles of plan health care outlined above, e.g. to permi the use of shorter or no crop rotation as a substitute for use of clean plantin material, or to permit the use of a dis ease-susceptible cultivar when resistan cultivars are available. These kinds o choices are usually dictated by econom ics.

Pesticides should be considered but a the last and not the first step toward plant-health care. Some biological con trols should also be considered as th last resort. The deliberate inoculation o plants with a mild strain of a plant viru to provide cross-protection against se vere strains is an example and is used today only where no alternative contro exists (Cook and Baker, 1983).

Considerable progress has been mad in recent years toward safer chemica pesticides and safer use of chemical pes ticides. The selectivity of pesticides ha been improved markedly as a means t minimize nontarget effects. Some mod ern classes of herbicides are effective a greatly reduced rates—a few grams pe hectare (fraction of an ounce per acre)— compared with earlier classes of herbi cides. The herbicide glyphosate, inva luable to conservation tillage systems, i quickly inactivated upon coming int contact with soil. Perhaps the greates advance in safer use of pesticides is th introduction of monitoring, simulation models, artificial intelligence, and a sys tems approach as a means to improv the timing and limit the number of ap plications of pesticides. Each of these advances and approaches can be ex pected to improve in the future and therefore chemicals will continue to play an important role in plant-health care.

Benefits of healthy plants

Pest control is usually and correctly justified economically on the basis of th higher yield and presumably highe profit for the farmer. Healthy plants ca also be justified sociologically on the ba sis of greater production of food. Thi was given emphasis in the theme of th

2nd International Congress of plant pathology held in Minneapolis, Minnesota, in 1973—Healthy Plants Healthy People! Healthy plants can also help make our managed ecosystems more sustainable (Cook, 1986a & b). Plants with a large and healthy root system help anchor soil in place, which limits soil erosion. They also return more organic matter to the soil and are more efficient in the uptake of mobile nutrients such as nitrates that otherwise might leach past the rooting zone and into the ground water. Healthy, vigorous plants are also more competitive with weeds, which can help reduce the need for herbicides. Healthy plants are also beneficial aesthetically.

References

1. Abel, P., R. S. Nelson, D. Barun, N. Hoffman, S. G. Rogers, R. T. Fraley, and R. N. Beachy. 1986. Delay of disease development in transgenic plants that express the tobacco mosaic virus coat protein gene. Science 232:738-743.
2. Allmaras, R. R., J. M. Kraft, and D. E. Miller. 1988. Soil compaction and crop residue effects on root health. Ann. Rev. Phytopathol. 26:In press.
3. Ashworth, L. J., Jr., D. P. Morgan, S. A. Gaona, and A. H. McCain. 1982. Polyethylene tarping controls Verticillium wilt in pistachios. Calif. Agric. 36(5-6):17-18.
4. Baker, K. F. 1962. Principles of heat treatment of soil and plant material. J. Aust. Inst. Agr. Sci. 28:118-126.
5. Baker, K. F. 1987. Evolving concepts of biological control of plant pathogens. Ann. Rev. Phytopathol. 25:67-85.
6. Baker, K. F., and R. J. Cook. 1974. Biological Control of Plant Pathogens, W. H. Freeman and Co., San Francisco, California. 433 pp. (Book, reprinted in 1982, Amer. Phytopathol. Soc., St. Paul, Minnesota).
7. Baker, K. F., and R. G. Linderman. 1979. Unique features of the pathology of ornamental plants. Ann. Rev. of Phytopathol. 17:253-277.
8. Baker, R. 1985. Biological control of plant pathogens: Definitions. pp. 25-39. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, New York, New York. 600 pp.
9. Beirner, B. P. 1967. Biological control and its potential. World Rev. Pest Control 6(1):7-20.
10. Biffen, R. H. 1906. Mendels law of inheritance and wheat breeding. J. Agric. Sci. 1:4-48.
11. Blakeman, J. P., and N. J. Fokkema. 1982. Potential for biological control of plant disease on the phylloplane. Ann. Rev. Phytopathol. 20:167-192.
12. Broadbent, P., and K. F. Baker. 1975. Soils suppressive to Phytophthora root rot in eastern Australia. pp. 152-157. In G. W. Bruehl (ed.). Biology and Control of Soil-borne Plant Pathogens. Amer. Phytopathol. Soc., St. Paul, Minnesota. 216 pp.
13. Burke, D. W., D. W. Miller, L. D. Holmes, and A. W. Barker. 1972. Counteracting bean root rot by loosening the soil. Phytopathology 62:306-309.
14. Chet, I., and R. Baker. 1981. Isolation and biocontrol potential of *Trichoderma hamatum* from soil naturally suppressive to *Rhizoctonia solani*. Phytopathology 71:286-290.
15. Cook, R. J. 1973. Influence of low plant and soil water potentials on diseases caused by soilborne fungi. Phytopathology 63:451-457.
16. Cook, R. J. 1980. Fusarium foot rot of wheat and its control in the Pacific Northwest. Plant Disease 64:1061-1066.
17. Cook, R. J. 1984. Root health: Importance and Relations to Farming Systems. In D. F. Bezdicek and J. F. Power (eds.). Organic Farming: Current Technology and Its Role in a Sustainable Agriculture. Amer. Soc. Agron. Special Publications: No. 46, Madison, Wisconsin, pp. 111-127.
18. Cook, R. J. 1985. Biological control of plant pathogens: theory to application. Phytopathology 75:25-29.
19. Cook, R. J. 1986a. Interrelationships of plant health and the sustainability of agriculture, with special reference to plant diseases. Amer. J. Alter. Agri. 1:19-24.
20. Cook, R. J. 1986b. Plant health and the sustainability of agriculture, with special reference to disease control by beneficial microorganisms. Biol. Agric. and Horticulture 3:211-232.
21. Cook, R. J. 1986c. Wheat management systems in the Pacific Northwest. Plant Disease 70:894-898.
22. Cook, R. J., Chairman. 1987. Research Briefing Panel on Biological Control in Managed Ecosystems. Committee on Science, Engineering, and Public Policy, National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. National Academy Press, Washington, DC. 12 pp.
23. Cook, R. J., and K. F. Baker. 1983. The Nature and Practice of Biological Control of Plant Pathogens. Amer. Phytopathol. Soc., St. Paul, Minnesota. 539 pp.
24. Cook, R. James, and A. D. Rovira. 1976. The role of bacteria in the biological control of *Gaeumannomyces graminis* by suppressive soils. Soil Biol. and Biochem. 8:269-273.
25. Cook, R. J., and D. M. Weller. 1987. Management of take-all in consecutive crops of wheat or barley. In I. Chet (ed.). Innovative Approaches to Plant Disease Control. John Wiley & Sons, Inc. pp. 41-76.
26. Cook, R. J., J. W. Sitton, and W. A. Haglund. 1987a. Increased growth and yield responses of wheat to reduction in the *Pythium* populations by soil treatments. Phytopathology 77:1192-1198.
27. Cook, R. J., D. M. Weller, and L. S. Thomashow. 1987b. Enhancement of root health and plant growth by rhizobacteria. In Molecular Strategies for Crop Protection. Alan R. Liss, Inc. pp. 125-134.
28. Corke, A. T. K. 1978. Interactions between microorganisms. Ann. Appl. Biol. 89:89-93.
29. Costa, A. S., and G. W. Muller. 1980. Tristeza control by cross protection: A U.S.-Brazil cooperative success. Plant Disease 64:538-541.
30. DeBach, P., ed. 1964. Biological Control of Insect Pests and Weeds. Reinhold, New York, New York. 844 pp.
31. Fulton, R. W. 1986. Practices and precautions in the use of cross protection for plant virus disease control. Ann. Rev. Phytopathol. 24:67-81.
32. Gerlagh, M. 1968. Introduction of *Ophiobolus graminis* into new polders and its decline. Neth. Jour. Plant Pathol. 74:(Suppl. 2):1-97.
33. Grogan, R. G. 1980. Control of lettuce mosaic with virus-free seed. Plant Disease. 64:446-449.
34. Hardison, J. R. 1976. Fire and flame for plant disease control. Ann. Rev. Phytopathol. 14:355-379.
35. Hering, T. F., R. J. Cook, and W.-h. Tang. 1987. Infection of wheat embryos by *Pythium* species during seed germination and the influence of seed age and soil matric potential. Phytopathology 77:1104-1108.
36. Hill, J. E. 1985. Methods for selecting beneficial Lactobacilli from swine. Advances in the Application of Microbiology to Agriculture. Pioneer Hi-Bred International, Inc., Microbial Genetics Division, Johnston, Iowa.
37. Holings, M. 1965. Disease control through virus-free stock. Ann. Rev. Phytopathol. 3:367-389.
38. Hwang, S. C., C. L. Chen, J. C. Lin. 1984. Cultivation of bananas using plantlets from meristem culture. HortScience 19:231-233.
39. Hyakumachi, M., and Tadao Ui. 1982. Decline of damping-off of sugarbeet seedlings caused by *Rhizoctonia solani* AG-2-2. Ann. of the Phytopathol. Soc. of Japn. 48(5):600-606.
40. Jones, D., and M. E. Solomon, eds. 1974. Biology in Pest and Disease Control. Brit. Ecol. Soc. Symp. 13. 398 pp.
41. Katan, J. 1981. Solar heating (solarization of soil for control of soilborne pests). Ann. Rev. Phytopathol. 19:211-236.
42. Kerr, A. 1980. Biological control of crown gall through production of agrocin 84. Plant Disease 64:25-30.
43. Kuć, J. 1982. Induced immunity to plant disease. Bioscience 32:854-860.
44. Lindow, S. W. 1983. Methods of preventing frost injury caused by epiphytic ice nucleation active bacteria. Plant Disease 67:327-333.
45. Lundholm, B., and M. Stackerud, eds. 1980. Environmental Protection and Biological Forms of Control of Pest Organisms. Swedish Natural Science Research Council Ecological Bulletins 31:1-171.
46. Lupton, F. G. H. 1984. Biological control: The plant breeder's objective. Ann. Appl. Biol. 104:1-16.
47. Marx, D. H. 1972. Ectomycorrhizae as biological deterrents to pathogenic root infections. Ann. Rev. Phytopathol. 10:429-454.
48. McBeth, C. W., and A. L. Taylor. 1944. Immune and resistant cover crops valuable in root-knot-infested peach orchards. Proc. Amer. Soc. Hort. Sci. 45:158-166.
49. Miller, D. E., and D. W. Burke. 1975. Effect of soil aeration on *Fusarium* root rot of beans. Phytopathology 65:519-523.
50. Papavizas, G. C., and R. D. Lumsden. 1980. Biological control of soilborne fungal propagules. Ann. Rev. Phytopathol. 18:389-413.
51. Papendick, R. I., and R. J. Cook. 1974. Plant water stress and development of *Fusarium* foot rot in wheat subjected to different cultural practices. Phytopathology 64:358-363.
52. Payne, C. C. 1988. Pathogens for the control of insects--where next? In R. K. S. Wood and M. J. Way (eds.). Biological Control of Pests, Pathogens, and Weeds: Developments and Prospects. The Royal Soc. Lond. pp. 115-248.
53. Phillips, R. E., R. L. Bevins. G. W. Thomas,

W. W. Freye, and S. H. Phillips. 1980. Notillage agriculture. Science 208:1108-1113.
54. Reis, E. M., R. J. Cook, and B. L. McNeal. 1982. Effect of mineral nutrition on take-all of wheat. Phytopathology 72:224-229.
55. Rickman, R. W., B. Klepper, and R. K. Belford. 1985. Developmental relationships among roots, leaves, and tillers in winter wheat. In W. Day and R. K. Atkins (eds.). Wheat Growth Modelling. Plenum Publishing. pp. 83-98.
56. Riggs, R. D., D. A. Slack, M. L. Hamblen, and L. Rakes. 1980. Nematode control studies in soybeans. Ark. Agric. Exp. Sta. Report series 252. 32 pp.
57. Rishbeth, J. 1979. Modern aspects of biological control of *Fomes* and *Armillaria*. Eur. J. For. Pathol. 9:331-340.
58. Roelfs, A. P. 1988. Genetic control of phenotypes in wheat stem rust. Ann. Rev. Phytopathol. 26:351-367.
59. Rouse, D. I. 1988. Use of crop-growth models to predict the effects of disease. Ann. Rev. Phytopathol. 26:183-201.
60. Rovira, A. D., and A. Simon. 1982. Integrated control of *Heterodera avenae*. EPPO Bull. 12:517-523.
61. Russell, R. S. 1975. Plant root systems: their function and interaction with soil. McGraw Hill, London. 298 pp.
62. Schenck, N. C., and M. K. Kellam. 1978. The influence of vesicular arbuscular mycorrhizae on disease development. Florida Agric. Exp. Sta. Bull. 798 (Technical):1-16.
63. Schroth, M. N., and J. G. Hancock. 1982. Disease-suppressive soil and root-colonizing bacteria. Science 216:1376-1381.
64. Shipton, P. J. 1977. Monoculture and soilborne plant pathogens. Ann. Rev. Phytopathol. 15:387-407.
65. Siegel, M. R., G. C. M. Latch, and M. C. Johnson. 1987. Fungal endophytes of grasses. Ann. Rev. Phytopathol. 25:293-315.
66. Slack, S. A. 1980. Pathogen-free plants by meristem culture. Plant Disease 64:15-17.
67. Smucker, A. J. M., and A. E. Erickson. 1987. Anaerobic stimulation of root exudates and disease of peas. Plant Soil 99:423-433.
68. Stolzy, L. H., J. Letey, L. J. Klotz, and C. K. Labanauskas. 1965. Water and aeration as factors in root decay of *Citrus sinensis*. Phytopathology 55:270-275.
69. Templeton, G. D., R. J. Smith, and D. O. TeBeest. 1986. Progress and potential of weed control with mycoherbicides. Rev. Weed Sci. 2:1-14.
70. Vaeck, M., A. Reynaerts, H. Hufte, S. Jansens, M. De Bueckeleer, C. Dean, M. Zabeau, M. van Montagu, and J. Leemans. 1987. Transgenic plants protected from insect attack. Nature 328:33-39.
71. Waage, J., and D. J. Greathead. 1988. Biological control: challenges and opportunities. In R. K. S. Wood and M. J. Way (eds.). Biological Control of Pests, Pathogens, ar Weeds: Developments and Prospects. Tl Royal Soc., London., pp 1-18.
72. Weinhold, A. R., J. W. Oswald, T. Bowma J. Bishop, and D. Wright. 1964. Influence green manures and crop rotation on comm scab of potato. Am. Potato Jour. 41:265-27
73. Weller, D. M., and R. J. Cook. 1983. Suppre sion of take-all of wheat by seed treatmen with fluorescent pseudomonads. Phytopat ology 73:463-469.
74. Weller, D. M., and R. J. Cook. 1987. Increas growth of wheat by seed treatments with fl orescent pseudomonads, and implications *Pythium* control. Can. J. Plant Pathol. 8:32 334.
75. Wilson, C. L., and P. L. Pusey. 1985. Potenti for the biocontrol of postharvest plant di eases. Plant Disease 69:375-378.
76. Zaag, D. E. van der. 1984. Reliability an significance of a simple method of estimatin the potential yield of the potato crop. Potat Research 27:51-73.

South Dakota reports on sustainable agriculture

A mail survey of 32 sustainable agriculture farmers in South Dakota drew a capsule picture of those operations, report Donald Taylor and Thomas Dobbs, agricultural economists at South Dakota State University. The 32 farmers have operations ranging from 350 to 1,000 acres and are highly diversified. Twenty-eight of them raise livestock commercially. The majority are seasoned veterans, Taylor and Dobbs say, with about 70 percent of the group having used "regenerative" practices for between 5 and 19 years.

Asked to list the reasons for their choice to farm with more sustainable methods, the farmers gave top ranking to soil stewardship, reduction of water pollution, growing a high-quality product, and reducing health risks from farm chemicals. Reduction in cash costs ranked on a lower level, although two-thirds of the farmers think regenerative farming is more profitable than conventional farming.

Fifty-five percent of the respondents reported using zero levels of all synthetic chemical inputs; the other 45 percent reported moderate use. Crop rotations and the use of legumes were listed as main practices for their regenerative systems. The two most important problems were identified as difficulties in finding markets and the lack of up-to-date information. The least significant problem listed was insect and disease control.

The South Dakota team will continue its research with on-farm interviews with about two dozen sustainable agriculture farmers to obtain more detailed insights on their practices. For more information, contact Taylor or Dobbs at the South Dakota State University Economics Department, Box 504A, Brookings, SD 57007.

ATTRA receives $900,000 in '89 budget for low-input work

ATTRA, the appropriate technology resource center operated in cooperation with the USDA in Memphis, Tennessee, was given $900,000 in the FY1989 federal budget signed on October 1, 1988. That is $150,000 more than the FY1988 funding, reported Bob Gray, policy consultant to the center.

"The increase shows Congressional commitment and will enable ATTRA to respond to the growing number of requests for low-input information from farmers and extension agents around the country," Gray said. Additional funds will be used to allow staff to spend more time on each request and to build the center's technical information resources. Rather than try to respond to all rural community economic development issues, in 1989 ATTRA will concentrate on low-input/sustainable agriculture information, Gray says. ATTRA can be reached at Agricenter International, 7777 Walnut Grove Road, Box 17, Memphis, TN 38119, (800) 346-9140.

Biological control of arthropod pests: Traditional and emerging technologies

Marjorie A. Hoy

Abstract. *Biological control of arthropod pests has a long history of useful practical application. Parasites, predators, and pathogens have been employed in many cases to control pest arthropods in an efficient, cost-effective, and permanent manner. The traditional tactics used in biological control (classical, augmentation, and conservation) remain vital and valuable tools in the biological control of pests for agricultural crops, range lands, forests, and glasshouses. New technologies offer promise. One emerging technique involves the genetic improvement of natural enemies of arthropods through selection, hybridization, or recombinant DNA technology.*

Key words: biocontrol agents, improvement, selection, hybridization, recombinant DNA technology, forests, rangelands, farmlands

Introduction

Crop yields in the United States are reduced by the impact of a variety of pests. Weeds are potentially the most damaging, followed by approximately 8000 species of insects and at a lower level by plant pathogens and nematodes (Batra, 1982). Control of pest insects has been achieved through chemical, cultural, and biorational controls, but biological control has unique advantages over the other tactics.

Biological control has been defined as the "actions of parasites, predators, and pathogens in maintaining another organism's density at a lower average than would occur in their absence" (DeBach, 1964). Some scientists would include host plant resistance, autocidal control, and pheromones under the category of biological control, but, while these biorational approaches to pest control have a biological basis, many investigators do not consider them to be biological control. Generally, biological control has been achieved by the use of one of three approaches--classical, augmentation, or conservation.

Classical biological control

"Classical" biological control is based on the importation of exotic natural enemies (parasites, predators, or pathogens) and their long-term establishment in the new environment, a strategy which may then provide long-term control of the target exotic pest arthropod or weed. This approach to biological control has been rewarding; hundreds of successful projects have reduced damage caused by a wide array of exotic pest arthropods and weeds (Laing and Hamai, 1976; Clausen, 1978). In addition, once a successful program is achieved in one location, the same natural enemies are frequently used to control the same pests elsewhere in other climatically similar locations. Around the world, about 170 successes were achieved between 1964 and 1976 by introducing natural enemies into a second site after they had been proven effective in the original geographic site of introduction (Luck et al., 1988). Natural enemy importation thus remains an important and effective tactic in pest management, particularly in the management of those arthropod and weed pests that are exotic. This approach to biological control, unfortunately, has received less support than it deserves.

While many scientists are worried about the extinction of animal and plant species in ecosystems, agricultural pest management specialists are concerned about *additions* to the fauna and flora of agroecosystems. In 1971, the U.S. Department of Agriculture established a task force to review the effectiveness of plant quarantines in preventing the entry of exotic pests and to quantify the risks associated with the entry of such pests and diseases (Sailer, 1983). A list of immigrant insects and related arthropods in the United States was compiled that categorized the immigrants as pests, beneficial species, and those of no known economic importance. The list continues to grow as additional species are found. At the conclusion of the 1971-1972 study, 1115 species were recognized to be of foreign origin and this number had increased to 1385 by 1977. Sixteen insect orders, mites (Acarina), and spiders (Araneae) are represented among the exotic arthropod species.

Foreign insect and mite species are considered to be responsible for a major part of all crop losses; one estimate is that they are responsible for 50 percent of such losses in California (Sailer, 1983). When viewed nationally, foreign species comprise 39 percent (235) of approximately 600 important arthropod pest species. Another 630 foreign species are on the list as pests of lesser importance, and an additional 420, or almost 25 percent of the immigrant fauna, are species of no known importance, while the remaining 398 are in some degree

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beneficial (Sailer, 1983). Exotic invaders include such pests as the Japanese beetle, European corn borer, Florida red scale, Rhodesgrass scale, spotted alfalfa aphid, gypsy moth, cottony cushion scale, California red scale, olive parlatoria scale, European red mite, imported southern red fire ant, Russian wheat aphid, and boll weevil.

Arthropods probably will continue to be added to the fauna of the United States at the rate of about eleven species per year, despite the efficacy of the national quarantine system (Sailer, 1983). Of the eleven, seven are likely to be pests of some importance, and about every third year a pest of major significance will be discovered. Assuming that many of these pests are not or cannot be eradicated, classical biological control will remain of crucial importance in controlling new exotic pests in forests, range lands, and agroecosystems.

Classical biological control has been actively practiced for about 100 years in the United States. Worldwide, approximately 2300 introductions directed against insect pests have provided complete biological control in about 100 cases (Ehler and Andres, 1983). Substantial control was provided in an additional 140 cases. Estimates of project outcomes that are successful range from 16 to 34 percent. Many factors affect success in classical biological control programs, including climate, natural enemies, habitat type, genetics, host compatibility, host phenology, and operational procedures. Thus, while classical biological control is effective and has yielded complete and lasting control in many important situations, there are several aspects of this pest management tactic that require additional research (Ehler and Andres, 1983; Hoy, 1985a). As noted by Huffaker (1971), "Many attempts have been only casual or have involved use of a particular natural enemy against unsuitable species or in unsuitable environments. The possibilities for controlling the notorious codling moth in this way, or the Mexican bean beetle, or the cotton boll weevil, for example, have only been explored superficially."

There are many views as to what the research priorities in classical biological control should be. There is little disagreement about the fact that this control has been under-exploited and underfunded. In one sense, it has been oversold; the dramatic cases in which complete biological control has been achieved through a small investment in research funds has, in my opinion, resulted in unrealistic expectations as to the resources needed to properly conduct classical biological control programs. This could be labeled the "cottony cushion syndrome."

The cottony cushion scale threatened the citrus industry in California in the late 1800s. This exotic species was suspected to have come from Australia. A very small amount of funding ($2000) was obtained to support a field agent's search for natural enemies in Australia in 1888. A parasite and a small lady beetle (then called *Vedalia*) were found attacking the scale in the Adelaide area of Australia, and 129 beetles were shipped to California. There they were placed on a small infested citrus tree enclosed in a mesh tent in January, 1889. By early April the scales were controlled on the caged tree and by early June over 10,000 beetles had been distributed to various southern California groves. By the end of 1889 the *Vedalia* beetle had cleared the scale pest from hundreds of acres of citrus. Unfortunately, most classical biological control programs probably require substantially more time and resources than were necessary for this project, yet such resources are rarely provided. However, if they were provided, both the rate of establishment and rate of success in classical biological control of arthropod pests and weeds could probably be increased, thus providing long-term, economical, and environmentally sound control of exotic pests (Huffaker, 1971; Tauber et al., 1985).

Augmentation

Augmentation involves efforts to increase populations or beneficial effects of natural enemies of both native and exotic pests (Rabb et al., 1976). A comprehensive review of augmentation in biological control is found in Ridgway and Vinson's (1977) book on *Biological Control by Augmentation of Natural Enemies.* Augmentation involves various techniques, including periodic release and environmental manipulation. Periodic releases may be labeled inundative or inoculative, depending upon the numbers of natural enemies released and the interval during which they are expected to provide control. Environmental manipulation may include provision of alternative, factitious hosts or prey, use of semiochemicals to improve natural enemy performance, provision of environmental requisites such as food or nesting sites, and modification of cropping practices to favor natural enemies. Augmentation has been particularly successful in glasshouse crops (Hussey and Scopes 1985).

Inundative releases are designed to control a pest by the actions of the released natural enemies, not by the actions of their progeny, and thus can be considered "biotic insecticides." Inundative releases are currently hampered by our limited ability to produce high quality, inexpensive, mass-reared natural enemies. Thus, advances in current research on synthetic diets, artificial hosts, quality control, and genetic manipulation could result in increased use of this tactic (King and Leppla, 1984; Hoy, 1986).

Another emerging technology is the use of semiochemicals to improve the efficacy of natural enemies in augmentation schemes. Parasitic insects use various chemical cues to locate their hosts (Nordlund et al., 1981). Recent reports indicate that learning can modify the responses of parasites to these chemicals (Lewis and Tumlinson, 1988). The complexity of host seeking behavior exhibited by arthropod natural enemies is only beginning to be understood and could lead to the more sophisticated use of natural enemy augmentation.

Conservation

Conservation involves protecting and *maintaining* natural enemy populations. Conservation is crucial if both native and exotic natural enemies are to be maintained in agricultural ecosystems. Most commonly, conservation involves

modifying pesticide application practices so that they occur only when the pest population exceeds specified levels. In some cases, conservation of natural enemies can be achieved by changing the active ingredient, rates, formulations, timing, and location of pesticide applications (Hull and Beers, 1985). Or, existing populations of natural enemies can be protected by maintaining refuges. According to Tauber et al (1985), "It is probable that the most dramatic increase in the utilization of biological control in agricultural IPM systems could come through the judicious use of selective pesticides in conjunction with effective natural enemies in specific cropping systems, in specific geographic regions. While we have some knowledge of pesticide selectivity, it is woefully inadequate to generally allow such precise usage." As long as key pests cannot be controlled biologically, culturally, or through host plant resistance, agricultural chemicals will be needed. Learning how to conserve natural enemies in the agroecosystem is an effective way to increase the use of biological control in agriculture (Hull and Beers, 1985).

Emerging technologies

Genetic manipulation of natural enemies of arthropods offers promise of enhancing their efficacy in agricultural cropping systems. Genetic manipulation of other beneficial arthropods, such as silkworms and honey bees, has been conducted for hundreds of years (Hoy, 1986). Such manipulation of biological control agents seems to be a logical extension of the domestication of crop plants and animals that has been part of agriculture for thousands of years, since many agricultural systems are artificial. As in crop breeding, three potential genetic manipulation tactics exist, i.e., artificial selection, hybridization (use of heterosis), and recombinant DNA (rDNA) techniques. To date, only artificial selection of arthropod natural enemies has been successfully employed, and the potential role of heterosis or rDNA technologies remains to be documented (Hoy, 1985c, 1986; Beckendorf and Hoy, 1985).

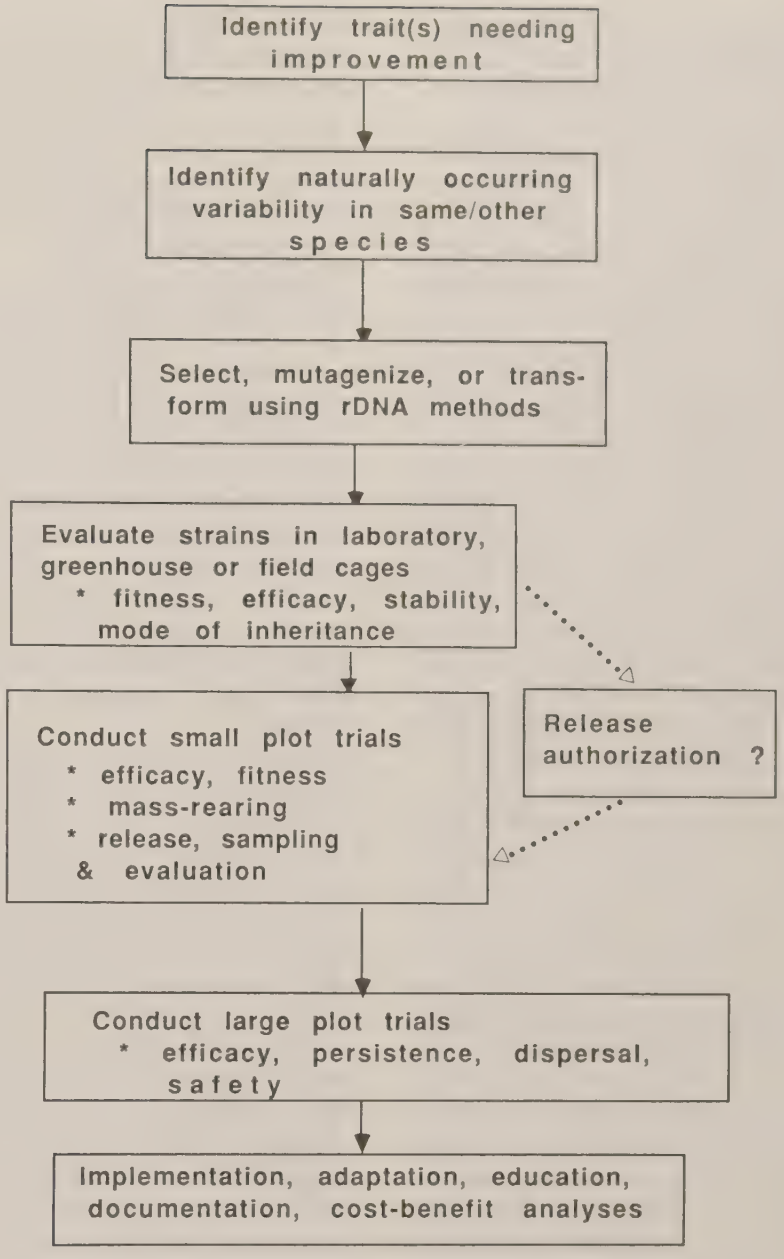
Identify trait(s) needing improvement
Identify naturally occurring variability in same/other species
Select, mutagenize, or transform using rDNA methods
Evaluate strains in laboratory, greenhouse or field cages
* fitness, efficacy, stability, mode of inheritance
Conduct small plot trials
* efficacy, fitness
* mass-rearing
* release, sampling & evaluation
Release authorization ?
Conduct large plot trials
* efficacy, persistence, dispersal, safety
Implementation, adaptation, education, documentation, cost-benefit analyses

Figure 1. Components of a genetic improvement project with arthropod natural enemies. Dashed lines indicate considerations if recombinant DNA methods are used as the method of genetic manipulation.

What are some of the constraints to initiating a genetic improvement project of arthropod natural enemies? First, the factors limiting the efficacy of the natural enemy must be identified (Figure 1). This means that a great deal must be known about the biology, ecology, and behavior of the natural enemy. This first step is extremely crucial, since improper identification of the trait needing improvement could lead to an expensive and time-consuming project of little practical value. Second, genetic variability must be available upon which one can select if using artificial selection. If such variability does not occur in natural populations, it must be provided for through mutagenesis or, perhaps, through recombinant DNA methods. Third, the "improved" natural enemy must be documented to be effective in the field. Finally, one must assume that the cost of the project will be justified by the benefits achieved.

Headley and Hoy (1986) recently reviewed the benefits and costs of an integrated mite management program in California almond orchards that involves the use of a genetically manipulated predatory mite. *Metaseiulus occidentalis* (Nesbitt) is an effective predator of spider mites in deciduous orchards and vineyards in western North America (Hoy, 1985b). It acquired resistance to organophosphorus insecticides (OPs) through natural selection in apple orchards in Washington and this resistance allowed the predator to survive in orchards even though an OP insecticide (azinphosmethyl or Guthion) was applied to control codling moth (Hoyt, 1969). In 1977, a genetic improvement project with *M. occidentalis* was initiated, with the goal of developing additional pesticide resistances in this predator in order to increase its usefulness in orchard and vineyard pest management programs.

Selection for resistance to carbaryl and permethrin was successful, and multi-resistant strains of *M. occidentalis* were obtained through laboratory crosses and additional selections. The laboratory-selected strains were then tested in small plot trials for two years, to determine whether they could become established in orchards or vineyards, survive the relevant pesticide applications in the field, spread, multiply, overwinter, and control the spider mites (Hoy, 1985b). The small plot trials were then followed by three years of research to learn how to implement the predators in an integrated mite management program in almonds (Hoy, 1985b; Headley and Hoy, 1986). Implementation involved developing mass rearing methods, monitoring methods, and learning how to use reduced rates and numbers of applications of insecticides and acaricides selective to this predator. The economic analysis suggested that almond growers who adopted the program would save $60 to $110/hectare. The programatic benefit/cost analysis suggested that the return on the research investment will range from 280 to 370 percent per year, depending upon the level of adoption by almond growers on the 158,000 hectares of almonds grown in California. This high rate of return on research investment was attributed, in part, to the fact that more than half of the research resources were allocated to field testing and implementation research (Headley and Hoy, 1986). Thus, genetic improvement with *M. occidentalis* has been shown to be efficacious and cost effective.

Genetic improvement projects with several phytoseiid species have included selection for enhanced fecundity, temperature tolerance, and non-diapause as well as pesticide resistances (Hoy, 1985c, Table 1). Selection projects are currently being conducted in the U.S.A., China, New Zealand, and France and field trials are being conducted with some of the selected strains. The successful implementation and economic analyses of costs and benefits of these genetically manipulated predatory mites will provide impetus to this tactic in biological control.

Genetic improvement projects with natural enemies of insects have been conducted for improved climatic tolerances, improved host finding ability, changes in host preference, improved synchronization with the host, insecticide resistance, non-diapause, and induction of thelytokous reproduction (Table 2), but to date none of these genetically manipulated natural enemies has been used in the field. Several current projects also are in progress and planned field trials will determine whether use of genetically manipulated insect natural enemies can be implemented in agricultural ecosystems. *Aphytis melinus*, a parasite of the California red scale, has been selecte for resistance to carbaryl and the resist ance level achieved appears to be suffi ciently high that field trials are justifie to evaluate this strain's efficacy in Cal ifornia citrus orchards (Rosenheim an Hoy, 1988). The walnut aphid parasite *Trioxys pallidus*, has been selected fo resistance to azinphosmethyl, and thi strain was tested in California walnu orchards during the 1988 growing sea son (Hoy and Cave, 1988). If *A. melinu* and *T. pallidus* are able to establish, su vive, parasitize their hosts, and success fully overwinter, then geneti improvement may be documented to b effective with insect parasitoids as wel as with predatory mites.

The potential for using rDNA tech nology in genetic manipulation of nat ural enemies of arthropods has bee reviewed by Beckendorf and Ho (1985). This new technology offers th possibility that genetic manipulatio could become more efficient and mor creative; beneficial genes isolated fro one species could be transferred to man if efficient transformation systems ca be found. This research has a number c steps; desirable genes must be identified cloned, inserted into natural enemies, b incorporated into their genome, be sta ble, be expressed in the appropriate tis sues and at the appropriate time, and b transmitted to the progeny. The trans formed natural enemy strain must the be fit and able to perform well in agri cultural systems (Figure 1). Issues re lating to the safety of releasing rDNA

Table 1. Genetic improvement of predatory mites (Acari: Phytoseiidae) through laboratory selection

Trait	Species	References
Fecundity	*Phytoseiulus persimilis*	Voroshilov & Kolmakova, 197
Non-diapause	*Metaseiulus occidentalis*	Hoy, 1984, Field & Hoy, 1986
Pesticide resistance		
	Amblyseius fallacis	Strickler & Croft, 1982
	Amblyseius nicholsi	Huang et al., 1987
	Metaseiulus occidentalis	Hoy & Knop, 1981, Roush & Hoy, 1981, Hoy, 198
	Phytoseiulus persimilis	Schulten & van de Klashor 1974, Avella et al., 1985
	Typhlodromus pyri	Markwick, 1986
Temperature tolerance		
	Phytoseiulus persimilis	Voroshilov, 1979

Table 2. Attributes of insect natural enemies that have been selected in the laboratory

Trait	Species	References
Host finding	*Trichogramma minutum*	Urquijo, 1946
		Landaluz, 1950
Host preference	*Horogenes molestae*	Allen, 1954
	Paratheresia claripalpis	Box, 1956
Host synchrony	*Cotesia melanoscela*	Weseloh, 1986
Improved climatic tolerance	*Dahlbominus fuscipennis*	Wilkes, 1942
	Aphytis lingnanensis	White et al., 1970
Increased fecundity	*Trichogramma fasciatum*	Ram & Sharma, 1977
	Dahlbominus fulginosus	Szmidt, 1972
	Dahlbominus fuscipennis	Wilkes, 1942
Insecticide resistance	*Macrocentrus ancylivorus*	Pielou & Glasser, 1952
	Bracon mellitor	Adams & Cross, 1967
	Aphytis melinus	Abdelrahman, 1973
		Rosenheim & Hoy, in press
	Trioxys pallidus	Hoy & Cave, 1988
	Chrysoperla carnea	Grafton-Cardwell & Hoy, 1986
Nondiapause	*Aphidoletes aphidimyza*	Gilkeson & Hill, 1986
Thelytoky	*Muscidifurax raptor*	Legner, 1987

manipulated arthropod natural enemies remain to be resolved. Safety questions will probably focus on three issues: 1) whether the transformed strain is stable, 2) whether the improved strain retains its host/prey specificity, and 3) whether the ecological range of the transformed strain has been altered. It will be important to remember that genetic improvement of arthropod natural enemies of insect and weed pests will be initiated because there is a serious pest problem. Risks and benefits of such genetic manipulation projects should be evaluated in terms of the costs and benefits of *not* doing the project.

Conclusions

In practice, effective biological control may require that several tactics be combined to achieve effective pest management. Thus, once an exotic natural enemy is established, specific efforts may be needed to conserve it. Alternatively, it may have to be released augmentatively if it is unable to persist in sufficient numbers, perhaps because it lacks a diapause or alternative hosts. Classical, augmentation, and conservation tactics should not be considered to be mutually exclusive. Arthropods have been pests in agriculture for more than 10,000 years; it is likely that they will remain serious pests of agriculture, even as it changes and evolves. New technologies should be examined to determine whether they can result in improved biological control.

Biological control is not being fully exploited as a method for the control of pest arthropods in forests, range lands, and agriculture (Huffaker, 1971; Tauber et al., 1985). Additional and continuing efforts should be made in the traditional classical, augmentation, and conservation approaches to biological control because the benefits associated with these approaches are already known to be substantial and can probably be improved. In addition, research efforts should be continued to combine and develop new and innovative approaches to biological control, including the genetic manipulation of natural enemies, the manipulation of natural enemy behavior through semiochemicals, and the development of improved artificial diets and improved rearing methods so that mass production for augmentative releases becomes economical. As summarized by Tauber et al. (1985), research needs in biological control "...form a continuum from the very basic to the applied..."

References

1. Abdelrahman, I. 1973. Toxicity of malathion to the natural enemies of California red scale, *Aonidiella aurantii* (Mask.) (Hemiptera:Diaspididae). Australian Journal of Agricultural Research 24:119-133.
2. Adams, C. H., and W. H. Cross. 1967. Insecticide resistance in *Bracon mellitor*, a parasite of the boll weevil. Journal of Economic Entomology 60:1016-1020.
3. Allen, H. W. 1954. Propagation of *Horogenes molestae*, an Asiatic parasite of the Oriental fruit moth, on the potato tuberworm. Journal of Economic Entomology 47:278-281.
4. Avella, M., D. Fournier, M. Pralavorio, and J. B. Berge. 1985. Selection pour la resistance a la deltamethrine d'une souche de *Phytoseiulus persimilis* Athias-Henriot. Agronomie 5:177-180.
5. Batra, S. W. T. 1982. Biological control in agroecosystems. Science 215:134-139.
6. Beckendorf, S. K., and M. A. Hoy. 1985. Genetic improvement of arthropod natural enemies through selection, hybridization or genetic engineering techniques. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems, Academic Press, Orlando, Florida. pp. 167-187.
7. Box, H. E. 1956. Battle against Venezuela's cane borer. I. Preliminary investigations and the launching of a general campaign. Sugar, 25-27:30,45.
8. Clausen, C. P., editor. 1978. Introduced Parasites and Predators of Arthropod Pests and Weeds: A World Review. Agricultural Handbook 480, USDA-ARS, Washington, DC.
9. DeBach, P., editor. 1964. Biological Control of Insect Pests and Weeds. Chapman and Hall, London, England. 844 pp.
10. Ehler, L.E., and L. A. Andres. 1983. Biological control: exotic natural enemies to control exotic pests. In C. L. Wilson and C. L. Graham (eds.). Exotic Plant Pests and North American Agriculture, Academic Press, New York, New York. pp. 395-418.
11. Field, R. P., and M. A. Hoy. 1986. Evaluation of genetically improved strains of *Metaseiulus occidentalis* (Nesbitt) (Acarina: Phytoseiidae) for integrated control of spider mites on roses in greenhouses. Hilgardia 54(2):1-32.
12. Gilkeson, L. A., and S. B. Hill. 1986. Genetic selection for and evaluation of non-diapause lines of predatory midge, *Aphidoletes aphidimyza* (Rondani) (Diptera: Cecidomyiidae). Canadian Entomologist 118:869-879.
13. Grafton-Cardwell, E. E., and M. A. Hoy. 1986. Genetic improvement of common green lacewing, *Chrysoperla carnea* (Neuroptera: Chrysopidae): selection for carbaryl resistance. Environmental Entomology 15:1130-1136.
14. Hagen, K. S., and J. M. Franz. 1973. A history of biological control. In R. F. Smith, T. E. Mittler, and C. N. Smith (eds.). History of Entomology. Annual Reviews, Inc., Palo Alto, California. pp. 433-476.
15. Headley, J. C., and M. A. Hoy. 1986. Benefit/cost analysis of an integrated mite management program for almonds. J. Econ. Entomol. 80:555-559.
16. Hoy, M. A. 1984. Genetic improvement of a biological control agent: multiple pesticide resistances and nondiapause in *Metaseiulus occidentalis* (Nesbitt) (Pytoseiidae). Proceedings VI International Congress of Acarology, Edinburgh, 1982, Acarology VI, Volume 2. D. A. Griffiths and C. E. Bowman, editors, Ellis Horwood Ltd., Halsted Press, New York, New York. pp. 673-679.
17. Hoy, M. A. 1985a. Improving establishment of arthropod natural enemies. In M.A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, Orlando, Florida. pp. 151-166.
18. Hoy, M. A. 1985b. Integrated mite management for California almond orchards. In W.

Helle and M. W. Sabelis (eds.). Spider Mites, Their Biology, Natural Enemies and Control. Volume 1B. Elsevier Science Publ., Amsterdam. pp. 299-310.
19. Hoy, M. A. 1985c. Recent advances in genetics and genetic improvement of the Phytoseiidae. Annual Review of Entomology 30:345-370.
20. Hoy, M. A. 1986. Use of genetic improvement in biological control. Agriculture, Ecosystems, and Environment 15:109-119.
21. Hoy, M. A., and F. E. Cave. 1988. Selection of the walnut aphid parasite, *Trioxys pallidus*, for resistance to azinphosmethyl. California Agriculture 42(4):4-5.
22. Hoy, M. A., and N. F. Knop. 1981. Selection for and genetic analysis of permethrin resistance in *Metaseiulus occidentalis*: genetic improvement of a biological control agent. Entomologia Experimentalis et Applicata 30:10-18.
23. Hoyt, S. C. 1969. Integrated chemical control of insects and biological control of spider mites on apple in Washington. Journal of Economic Entomology 62:74-86.
24. Huang, M.-D., J.-J. Xiong, and T.-Y. Du. 1987. The selection for and genetical analysis of phosmet resistance in *Amblyseius nicholsi*. Acta Entomologica Sinica 30(2):133-139.
25. Huffaker, C. B., editor. 1971. Biological Control. Plenum Press, New York, New York. 511 pp.
26. Hull, L. A., and E. H. Beers. 1985. Ecological selectivity: modifying chemical control practices to preserve natural enemies. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, Orlando, Florida. pp. 103-122.
27. Hussey, N. W., and N. Scopes, editors. 1985. Biological Pest Control, The Glasshouse Experience. Cornell University Press, Ithaca, New York. 240 pp.
28. King, E. G., and N. C. Leppla, editors. 1984. Advances and Challenges in Insect Rearing. USDA, ARS (Southern Region), New Orleans, Louisiana. 305 pp.
29. Laing, J. E., and J. Hamai. 1976. Biological control of insect pests and weeks by imported parasites, predators and pathogens. In C. B. Huffaker and P. S. Messenger (eds.). Theory and Practice of Biological Control. Academic Press, New York, New York. pp. 685-743.
30. Landaluz, P. U. 1950. Aplicacion de la genetica al aumento de la eficacia del *Trichogramma minutum* en la lucha biologica. Bolet. Patol. Vegetal Entomol. Agric. 18:1-12.
31. Legner, E. F. 1987. Transfer of thelytoky to arrhenotokous *Muscidifurax raptor* Girault and Sanders (Hymenoptera: Pteromalidae). Canadian Entomologist 119:265-271.
32. Lewis, W. J., and J. H. Tumlinson. 1988. Host detection by chemically mediated associative learning in a parasitic wasp. Nature 331:257-259.
33. Luck, R. F., B. M. Shepard, and P. E. Kenmore. 1988. Experimental methods for evaluating arthropod natural enemies. Annual Review of Entomology 33:367-391.
34. Markwick, N. P. 1986. Detecting variability and selecting for pesticide resistance in two species of phytoseiid mites. Entomophaga 31:225-236.
35. Nordlund, D. A., R. L. Jones, and W. J. Lewis, editors. 1981. Semiochemicals, Their Role in Pest Control. W. J. Wiley, Chichester.
36. Pielou, D. P., and F. R. Glasser. 1952. Selection for DDT resistance in a beneficial insect parasite. Science 115:117.
37. Rabb, R. L., R. E. Stinner, and R. van den Bosch. 1976. Conservation and augmentation of natural enemies. In C. B. Huffaker and P. S. Messenger (eds.). Theory and Practice of Biological Control. Academic Press, New York, New York. pp. 233-254.
38. Ram, A., and A. K. Sharma. 1977. Selective breeding for improving the fecundity and sex ratio of *Trichogramma fasciatum* (Perkins) (Trichogrammatidae: Hymenoptera), an egg parasite of lepidopterous hosts. Entomology 2:133-137.
39. Ridgway, R. L., and S. B. Vinson. 1977. Biological Control by Augmentation of Natural Enemies. Plenum Press, New York, New York. 480 pp.
40. Robertson, J. G. 1957. Changes in resistance to DDT in *Macrocentrus ancylivorus* Rohw. (Hymenoptera: Braconidae). Canadian Journal of Zoology 35:629-633.
41. Rosenheim, J. A., and M. A. Hoy. 1988. Genetic improvement of a parasitoid biological control agent: artificial selection for insecticide resistance in *Aphytis melinus* (Hymenoptera: Aphelinidae). Journal of Economic Entomology.
42. Roush, R. T., and M. A. Hoy. 1981. Genetic improvement of *Metaseiulus occidentalis*: selection with methomyl, dimethoate, and carbaryl and genetic analysis of carbaryl resistance. Journal of Economic Entomology 74:138-141.
43. Sailer, R. I. 1983. History of insect introductions. In C. L. Wilson and C. L. Graham (eds.). Exotic Plant Pests and North American Agriculture. Academic Press, New York, New York. pp. 15-37.
44. Schulten, G. G. M., and G. van de Klashorst. 1974. Genetics of resistance to parathion and demeton-s-methyl in *Phytoseiulus persimilis*. A. H. (Acari: Phytoseiidae). Proceedings 4th International Congress of Acarology. pp. 519-524.
45. Simmonds, F. J. 1947. Improvement of the sex-ratio of a parasite by selection. Canadian Entomologist 79:41-44.
46. Strickler, K. A., and B. A. Croft. 1982. Selection for permethrin resistance in the predatory mite *Amblyseius fallacis* Garman (Acarina: Phytoseiidae). Entomologia Experimentalis et Applicata 31:339-345.
47. Szmidt, A. 1972. Studies on the efficiency of various strains of the parasite *Dahlbominus fuscipennis* (Zett.) (Hymenoptera, Chalcidoidea) under natural condition. Ekol. Pol. 20:299-313.
48. Tauber, M. J., M. A. Hoy, and D. C. Herzog. 1985. Biological control in agricultural IPM systems: a brief overview of the current status and future prospects. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, Orlando, Florida. pp. 3-9.
49. Urquijo, P. 1946. Selecion des estirpes de *Trichogramma minutum* Riley de maxima effectividad parasitaria. Boln. Patol. Veg. Ent. Agric. 14:199-216.
50. Voroshilov, H. V. 1979. Heat-resistant lines of the mite *Phytoseiulus persimilis* H.-H. Genetika 15(1):70-76.
51. Voroshilov, N. V., and L. I. Kolmakova. 1977. Heritability of fertility in a hybrid population of *Phytoseiulus*. Genetika 13(8):1496-1497.
52. Weseloh, R. M. 1986. Artificial selection for host suitability and developmental length of the gypsy moth (Lepidoptera: Lymantriidae) parasite, *Cotesia melanoscela* (Hymenoptera: Braconidae). J. Econ. Entomol. 79:1212-121
53. White, E. B., P. DeBach, and M. J. Garber 1970. Artificial selection for genetic adaptation to temperature extremes in *Aphytis lingnanensis* Compere (Hymenoptera: Aphelinidae). Hilgardia 40(6):161-192.
54. Wilkes, A. 1942. The influence of selection on the preferendum of a chalcid (*Microplectron fuscipennis* Zett.) and its significance in the biological control of an insect pest. Proc. Royal Society London, Series B 130:400-41

Low-input farming asset for 21st century

"Our inability to accurately predict future trends [for agriculture] suggests the need for system resiliency," Virginia Polytechnic Professor Daniel Taylor told 500 natural resource professionals meeting in Washington, DC, to assess resource trends for the 21st century. Taylor said that conventional agriculture, which is characterized by monoculture, chemical dependence, high technology, and concentrated ownership, needs to evolve into a system with more "flexibility and robustness." That means more integration of animal agriculture with cropping and a decrease of chemical dependency, he said.

Pesticide use in the U.S. rose rapidly from 150 million pounds per year in 1964 to 500 million pounds in 1982, but "we expect to see that use level off and then decline," Taylor predicted. Fertilizer use has already peaked and is declining, he reported, with water quality issues a major factor in the change.

"As economist Kenneth Boulding said, 'while we have to be prepared to be surprised by the future, we do not have to be dumbfounded,'" Taylor concluded. He recommended that the 1990 Farm Bill be used to help create more resilient farming systems. The remarks came as part of a three-day conference, "Natural Resources for the 21st Century," sponsored by the American Forestry Association in mid-November, 1988.

Biological control of weeds

George E. Templeton

Abstract. *A shortage of effective, non-chemical pest control measures is a major constraint to more widespread adoption of sustainable agricultural practices. Overcoming this constraint with biological pest control tactics appears to be an attainable goal but will require substantial public sector support. Biological agents that are self-perpetuating do not offer profit incentive to private industry. On the other hand, microbial pesticides, which do require annual application, often are so highly specific for particular pests that the private sector is unable to risk venture capital for their development. Collaboration between public- and private-sector scientists is essential for biological pesticide development. In the U.S., a model working relationship for technology transfer between the private and public sector has been achieved with two commercial mycoherbicides, Collego™ and DeVine™. The model illustrates the strengths of the public sector for creating and storing fundamental knowledge of biological interactions at the organismal and ecosystem levels, also the capability of the private sector for large-scale production of fungi, for drying labile, living products, for effective patent protection, for satisfying EPA registration requirements, and for the commercial distribution, marketing and servicing of agricultural products. From three perspectives--biological, technical, and commercial--the success of Collego™ and DeVine™ has provided a definite step in the quest for low-cost weed control methods that are not hazardous to the environment nor in ground water. These successes also provide a model for an approach to reducing the dependence of agriculture upon chemical herbicides, the most extensively used chemical pesticides in agricultural production, likewise a useful insight toward technology that can lead to more widespread adoption of low-input, environmentally compatible and sustainable agricultural production.*

Key words: spores, plant pathogen, *Colletotrichum gloeosporioides*, Collego™, DeVine™, weed killer, northern jointvetch, discovery, development, mycoherbicides

Introduction

A shortage of effective, non-chemical pest control measures is a major constraint to more widespread adoption of sustainable agricultural practices (Barron, 1981). Overcoming this constraint with biological pest control tactics, however, appears to be an attainable goal (Anonymous, 1978). A growing body of knowledge and practical experience with biological pest control appears to lend support for the idea that biological pest control is potentially capable of substantially reducing and perhaps eventually eliminating agriculture's dependence upon chemical pesticides in future agricultural production (Charudattan, 1984, 1986, 1987; Freeman and Charudattan, 1981; Hasan, 1974; National Academy of Science, 1987).

Support for the biological control idea comes from several positive developments. Specific achievements during the past decade appear to offer representative models for further implementation of the concept (TeBeest and Templeton, 1985). A reasonable regulatory framework has been developed to guide field evaluation of biologicals (Anonymous, 1982, 1983; Charudattan, 1982). Private industry now realizes that there can be a profit incentive for development of certain microbes as biological pesticides (Bowers, 1982, 1986; Churchill, 1982; Kenney et al., 1979). Interdisciplinary teamwork is increasingly recognized as the sensible way to achieve success in biological control. Effective technology transfer between public sector scientists and private industry is clearly essential for achieving practical commercial success with biological pesticides (Templeton et al., 1980; U.S. Department of Agriculture, 1983).

Furthermore, genetic engineering techniques and advances in other aspects of biotechnology can enhance our ability to manipulate biological agents practically and make possible new tactics (Charudattan, 1985; National Academy of Science, 1987; Peberdy, 1983). Achieving widespread adoption of sustainable agricultural practices appears more promising because of the new emphases and potential of biological control tactics for reducing insects, plant diseases, weeds and nematodes.

Biological control tactics

Three common approaches are:

1. Classical Biological Control -- Importation of exotic natural enemies for release, dissemination, and self-perpetuation on a target pest population.

2. Integrated Pest Management (IPM) -- Conservation and enhancement of indigenous natural enemies.

3. Biological Pesticides -- Augmentation of indigenous natural enemies with reared or cultured agents.

Each tactic is scientifically sound and has been demonstrated to work. Unlike chemical pesticides, biological tactics have no known non-target effects. All have potential for use in sustainable agricultural production. The choice of tactics to use is based upon several factors: whether the pest is introduced or indigenous, whether it occurs in high-value

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crops or in low-value rangelands, and what level of control is required to achieve acceptable yield and quality (Templeton, 1982; Templeton and Smith, 1977; Templeton et al., 1979). Successful deployment of any tactic is dependent upon fundamental knowledge of biological interactions between the pest and its natural enemies at the organismal and ecosystem levels.

The tactics most often successful for weed control have been the classical tactic of importing exotics and the biopesticide tactic of augmentation of indigenous natural enemies. The IPM tactic has been more important for insect and disease control than it has with weed control.

Biological herbicides

Biological herbicides have particular potential for sustainable agricultural production of annual crops. They can be used as practical alternatives to chemical herbicides, the most extensively used group of agriculture pesticides and one of the more expensive inputs in crop production.

Biological herbicides are indigenous weed pathogens, commercially produced, applied annually to a specific population in a site and integrated into existing pest management systems. They can have profit incentives for industry (Bowers, 1982, 1986; Guest, 1984; Kenney et al., 1979).

Only two biological herbicides, Collego™ and DeVine™ have been commercialized and successfully used (Ridings, 1986; Templeton et al., 1984). They are termed mycoherbicides because they are fungal plant pathogens of specific weed hosts. They are applied as sprays for post emergent weed control. Collego™ contains *Colletotrichum gloeosporioides* f. sp. *aeschynomene* for control of northern jointvetch in rice and soybeans, and DeVine™ is a formulation of *Phytophthora citrophthora* for control of stranglervine in citrus orchards. A third mycoherbicide is produced and has been distributed free by the Noble Foundation since 1969 (Griffith, 1981). A fourth, *Alternaria* on sicklepod, is expected to be commercialized in 1989 or 1990 by the Mycogen Corporation of San Diego, California. A fifth, *Colletotrichum gloeosporioides* f. sp. *malvae* on *Malva*, is expected to be released in Canada in 1989 or 1990 by Philom Bios Corporation. Abroad, the New South Wales Department of Agriculture is seeking a licensee to commercialize a mycoherbicide for control of spiny cocklebur in Australia, and one has been developed in the People's Republic of China for control of dodder. Projects to find weed disease fungi and develop them for use as mycoherbicides are known to be active in Australia, Brazil, Canada, China, Denmark, England, Israel, Italy, Japan, The Netherlands, Philippines, Scotland, South Africa, and Switzerland. It is believed that other countries are active, especially countries in Eastern Europe, but the facts have not been widely publicized.

A pattern for discovery and development of mycoherbicides is emerging from these efforts in the U.S. and abroad. Fungi are being discovered and evaluated for biological feasibility by public-sector scientists in the laboratory, controlled environments and small-scale field tests. This technology is transferred to the private sector for production scale-up, drying and formulation, large-scale field evaluation, EPA registration and marketing. This partnership evolves naturally, and it recognizes the strength of the public sector for creating and storing fundamental knowledge of biological interactions at the organismal and ecosystem levels by the large network of scientific expertise, facilities and instrumentation located throughout the nation's universities, agricultural experiment stations, and U.S. Department of Agriculture. It recognizes also the capability of the private sector for large-scale production of fungi by fermentation, for drying of comparatively labile, living biological products, for patent protection, for satisfying EPA registration requirements, and for commercial distribution, marketing and servicing agricultural products.

Some economic realities also are apparent from the mycoherbicide projects which bear upon their future availability and contribution to sustainable agricultural production. Mycoherbicides generally are less costly to develop yet less profitable to commercialize than broa spectrum chemical herbicides (Ayers al., 1977). They often can be produce and formulated in existing fermentatic facilities at comparatively low cos (Churchill, 1982; Kenney et al., 1979 However, specificity is more the ru than the exception with biologicals, they are highly specific for a single wee problem and may have relatively sma market potential. Specificity, howeve also leads to obvious advantages fro environmental and safety perspectiv but an obvious disadvantage from th economic perspective. The emergin pattern for discovery and developme of mycoherbicides is for the public secto to bear the cost of discovery and eva uation as an incentive to private industr to commercialize them. Commercial zation of the mycoherbicide Collego™ is an example.

Discovery and development of a model mycoherbicide

Collego™ is a dry formulation spores of a strain of the indigenous fu gus *Colletotrichum gloeosporioid* (Penz.) Sacc. that has been used com mercially since 1982 as a selective pos emergence mycoherbicide to contr northern jointvetch in rice and soybea fields in Arkansas (Templeton et a 1984). It has been termed the "arch typal" mycoherbicide by some becau it illustrates the biological, technical an commercial feasibility of using specif indigenous fungal pathogens to kill n tive weeds in annual crops, especial crops that are intensively managed an have relied heavily in the past upo chemical pesticides in comprehensi pest control strategies. It is a superi substitute for and has, in fact, replace a chemical herbicide for control of th specific weed.

The development of Collego™ also i lustrates the value of collaborative a rangements between and amon disciplines and agencies, also technolog transfer between the public and priva sectors for effective commercializatio of mycoherbicides. It was developed b plant pathologists and veterinary p thologists at the University of Arkans

Agricultural Experiment Station, weed scientists of the U.S. Department of Agriculture Agricultural Research Service and fermentation scientists, registration specialists and marketing personnel of The Upjohn Pharmaceutical Company (Bowers, 1982, 1986; Daniel et al., 1973; Smith, 1982, 1986; TeBeest and Templeton, 1985; Templeton et al., 1981; Templeton et al., 1984). The product is now marketed by Ecogen Inc., which purchased it from Nor-Am Chemical Company. Nor-Am had obtained it from Upjohn, which still produces and packages it under contract with Ecogen.

Collego™ required thirteen years to develop from discovery to commercial sales. The disease was found in weed research plots by a USDA weed scientist developing cost/benefit data on control with the chemical herbicide 2,4,5-T. It killed transplanted weed seedlings before the chemical herbicide was to be applied. Subsequent surveys and research revealed the causal agent to be a fungus that occurs naturally wherever the weed is found but normally produces only inconspicuous lesions on stems and pods of the leguminous weed host.

Plant pathologists studied the fungus in the laboratory and greenhouse. It was isolated in pure culture and inoculated on seedling plants in controlled environments. Media for artificial culture were formulated to obtain ample supplies of the organism for experimentation. Seedling weeds and crop plants and ecologically important plants were sprayed with suspensions of the fungus spores and placed in moist conditions for infection and disease development. These studies revealed the native fungus to be lethal to the target weed and highly specific for this native host, also genetically stable. Other plants were not infected (Daniel et al., 1973). More recent studies indicate that English peas are susceptible to infection, but Collego™ is not marketed where this crop is grown. Spores of the fungus were found to be labile and unable to persist long if not on nutrient media or on the host (TeBeest, 1982; TeBeest et al., 1978a; TeBeest et al., 1978b). Extensive tests with animals conducted by a veterinary pathologist showed that the fungus is not toxic nor infectious (Beasley et al., 1975). Field plot tests with fungus spores sprayed as a chemical herbicide successfully controlled the weed, and levels of the fungus quickly returned to background levels after application (Templeton et al., 1981). These studies and the animal safety tests made it possible to obtain an Experimental Use Permit from the U.S. Environmental Protection Agency for large-scale tests on natural populations of the weed in growers' fields.

Biotechnology support for large-scale production and formulation of the fungus for large-field tests with the fungus was provided by The Upjohn Company. They first scaled-up the production of spores to large fermentation tanks and provided wet pastes of spores that would remain viable for only a few days (Churchill, 1982). Their subsequent research resulted in a dry spore formulation that has two or three years shelf-life.

Aerial applications of spores in water suspensions over a period of eight growing seasons confirmed effectiveness and safety of this natural weed killer when temporarily augmented to lethal levels in weed-infested rice and soybean fields (Templeton et al., 1981; Smith, 1986). The TUCO Division of the Upjohn Company applied for and received EPA registration in 1982 and began commercial sales. At the same time an exemption from the requirement of a residue tolerance was issued. Grower experience with the product has been excellent, and sale of the product has been a financially successful venture. Collego™ is successful from three perspectives--biological, technical and commercial. The scientific and commercial interest in mycoherbicides and other biopesticides in the U.S. and abroad is a definite step in the quest for low-cost pest control methods that are not hazardous to the environment or ground water. The prospect has been raised that a major barrier can be overcome and more widespread adoption of sustainable agricultural practices can be achieved.

References

1. Anonymous. 1978. Biological agents for pest control -- status and prospects. U.S. Dept. of Agric. U.S. Printing Office, Washington, DC. 138 pp.
2. Anonymous. 1982. Pesticide registration: Proposed data requirements, Part III. Proposed rules. Federal Register 47(227):53112-53127.
3. Anonymous. 1983. Pesticide registration: Proposed data requirements, corrections. Federal Register 48(12):2142-2147.
4. Ayers, J. H., T. A. Blue, R. R. Bramhall, T. J. Braunstein, E. E. Davis, J. I. DeGraw, T. E. Elward, R. E. Inman, O. H. Johnson, E. B. Leaf, F. L. Offensend, and P. S. Stent. 1977. New, innovative pesticides: An evaluation of incentives and disincentives for commercial development by industry. Stanford Research Institute, Report to the U.S. Environmental Protection Agency. Office of Pesticide Programs Criteria and Evaluation Division. Washington, DC. EPA Contract 68-01-2487.
5. Barron, K. C. 1981. Are pesticides really necessary? Regnery Gateway, Inc. Book Publishers, Chicago, Illinois. 245 pp.
6. Beasley, J. N., L. T. Patterson, G. E. Templeton, and R. J. Smith, Jr. 1975. Responses of animals to a fungus used as a biological herbicide. Ark. Farm Res. 24(6):16.
7. Bowers, R. C. 1982. Commercialization of microbial biological control agents. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens, pp. 157-173. John Wiley and Sons, New York, New York. 293 pp.
8. Bowers, R. C. 1986. Commercialization of Collego™ -- an industrialist's view. Weed Sci. 34 (Suppl. 1):24-25.
9. Charudattan, R. 1982. Regulation of microbial biological control agents. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens, pp. 175-188. John Wiley and Sons, New York, New York. 293 pp.
10. Charudattan, R. 1984. Microbial control of plant pathogens and weeds. J. Georgia Entomological Soc. Supp. 2, Vol. 19(31):40-62.
11. Charudattan, R. 1985. The use of natural and genetically altered strains of pathogens for weed control. In D. Herzog and M. Hoy (eds.). Biological Control in Agricultural IPM Systems. Academic Press, New York, New York. pp. 347-372.
12. Charudattan, R. 1986. Integrated control of water-hyacinth [*Eichornia crassipes* (Mart.) Solms] with a pathogen, insects and herbicides. Weed Sci. 34 (Suppl. 1):26-30.
13. Charudattan, R. 1987. Fungi help fight the war of the weeds. In Research 87 Biocontrol. University of Florida, Agricultural Experiment Station, Gainesville, Florida. pp. 38-39.
14. Churchill, B. W. 1982. Mass production of microorganisms for biological control. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens, pp. 137-156. John Wiley and Sons, New York, New York. 293 pp.
15. Daniel, J. T., G. E. Templeton, R. J. Smith, Jr., and W. T. Fox. 1973. Biological control of nothern jointvetch in rice with an endemic fungal disease. Weed Sci. 21:303-307.
16. Freeman, T. E., and R. Charudattan. 1981. Biological control of weeds with plant pathogens. Prospectus - 1980. In E. S. Del Fosse (ed.). Proc. Fifth Intl. Symp. on Biological Control of Weeds, pp. 293-299. Commonwealth Scientific and Industrial Research Organization, Australia. 649 pp.
17. Griffith, C. H. 1981. Personal communication. The Noble Foundation, Ardmore, Oklahoma 73401.

18. Guest, R. T. 1984. The IR-4 biorational registration program. Abstr. Weed Sci. Soc. of Am. p. 74.
19. Hasan, S. 1974. Recent advance in the use of plant pathogens as biological control agents of weeds. Pest Articles and News Summaries 20:437-443.
20. Kenney, D. S., K. E. Conway, and W. H. Ridings. 1979. Mycoherbicides - potential for commercialization. In L.A. Underkofler (ed.). Developments in Industrial Microbiology. Society for Industrial Microbiology, Arlington, Virginia. pp. 123-130.
21. National Academy of Science. 1987. Research Briefings 1987. Report of the Research Briefing Panel on Biological Control in Managed Ecosystems. National Academy Press, Washington, DC. 12 pp.
22. Peberdy, J. R. 1983. Genetic recombination in fungi following protoplast fusion and transformation. In J. E. Smith (ed.). Fungal Differentiation. Marcel Dekker, New York, New York. pp. 559-581.
23. Ridings, W. H. 1986. Biological control of stranglervine (*Morrenia odorata* Lindl.) in citrus - a researcher's view. Weed Sci. Suppl. 34:Supp. 1.
24. Smith, R. J., Jr. 1982. Integration of microbial herbicides with existing pest management programs. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens, pp. 189-203. John Wiley and Sons, New York, New York. 293 pp.
25. Smith, R. J., Jr. 1986. Biological control of northern jointvetch [*Aeschynomene virginica* (L.) B.S.P.] in rice and soybeans - a researcher's view. Weed Sci. 34 (Suppl. 1):17-23.
26. TeBeest, D. O. 1982. Survival of *Colletotrichum gloeosporioides* f. sp. *aeschynomene* in rice irrigation water and soil. Plant Dis. 66:469-472.
27. TeBeest, D. O., and G. E. Templeton. 1985. Mycoherbicides: Progress in the biological control of weeds. Plant Dis. 69:6-10.
28. TeBeest, D. O., G. E. Templeton, and R. J. Smith, Jr. 1978a. Decline of a biocontrol fungus in field soil during winter. Ark. Farm Res. 27(1):12.
29. TeBeest, D. O., G. E. Templeton, and R. J. Smith, Jr. 1978b. Temperature and moisture requirements for development of anthracnose on northern jointvetch. Phytopathology 68:389-393.
30. Templeton, G. E. 1982. Biological herbicides: Discovery, development, deployment. Weed Sci. 30:430-433.
31. Templeton, G. E. 1982. Status of weed control with plant pathogens. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens, pp. 29-44. John Wiley and Sons, New York, New York. 293 pp.
32. Templeton, G. E. 1986. Mycoherbicide research at the University of Arkansas - past, present and future. Weed Sci. 34 (Suppl. 1):35-37.
33. Templeton, G. E., and R. J. Smith, Jr. 1977. Managing weeds with pathogens. In J. G. Horsfall and E. G. Cowling (eds.). Plant Disease: An Advanced Treatise. Vol. I. Academic Press, New York, New York. pp. 167-176.
34. Templeton, G. E., R. J. Smith, Jr., and W. Klomparens. 1980. Commercialization of fungi and bacteria for biological control. Biocontrol News Inf. 1(4):291-294.
35. Templeton, G. E., R. J. Smith, Jr., D. O. TeBeest, J. N. Beasley, and R. A. Klerk. 1981. Field evaluation of dried fungus spores for biocontrol of curly indigo in rice and soybean Ark. Farm Res. 30(6):8.
36. Templeton, G. E., D. O. TeBeest, and R. Smith, Jr. 1979. Biological weed control wi mycoherbicides. Annu. Rev. Phytopath 17:301-310.
37. Templeton, G. E., D. O. TeBeest, and R. Smith, Jr. 1984. Biological weed control rice with a strain of *Colletotrichum gloeosp rioides* (Penz.) Sacc. used as a mycoherbicid Crop Protection 3(4):411-424.
38. United States Department of Agricultur 1983. Proceedings of the Interdisciplinary B ological Control Conference, February 15-1 1983. Las Vegas, Nevada. USDA Cooperati State Research Service, Washington, DC. 10 pp.

Farm chemicals near top of farmer concerns in Iowa

Concern about farm chemicals in drinking water ranked just after farm prices and the federal budget deficit as matters of concern in the 1988 Iowa Farm and Rural Life Poll conducted by Iowa State University Extension. Nearly three out of four respondents were concerned about pesticides compared to eight out of ten concerned about farm price and deficit issues, says the October, 1988, report. Seven out of ten farmers ranked adverse health effects from exposure to agricultural chemicals as major concerns.

Nearly three out of four farmers responding agreed that economic development that results in the destruction of wildlife habitat should be stopped. But respondents were divided on whether the government should require all farmers to implement an approved conservation plan, with 45 percent supporting that idea, but 35 percent disagreeing, and 20 percent uncertain.

Overall, the Iowa farm operators thought that farm financial conditions had improved during the past two years, and 40 percent believe their economic prospects will improve over the next five years. That is twice as much optimism as reported in 1982, 1984, or 1986, says Paul Lasley, the Extension Sociologist who is chief author of the report. For information, contact Lasley at the Iowa State Extension, Ames, IA 50011.

EPA adopts new pesticide policy for processed foods

On October 12, 1988, the Environmental Protection Agency issued a new policy which loosens the "zero-risk" standard for pesticides that increase in concentration during food processing. In the future, pesticides will be approved for use if they pose a "negligible risk." That is defined as increasing the odds of cancer by no more than 1 in 1 million. The regulation is a change to the rule called the "Delaney Clause," formulated by Rep. James Delaney in 1958, which bars any food additive found to cause cancer in man or animal.

At least a dozen pesticides which concentrate in processed foods have been kept off the market even though they pose much lower cancer risk than older chemicals, the *Washington Post* said in its report on the action. Older chemicals may remain on the market simply because the EPA lacks data needed to ban them. EPA spokesman Edward Gray said that the new rule will allow the agency to "make better comparative decisions about which chemicals to keep and which not to keep." Natural Resources Defense Council staff argue that the rule places consumers at greater risk unless old pesticides are, in fact, taken off the market.

CASST™ herbicide (Alternaria cassiae): A case history of a mycoherbicide

James S. Bannon

Abstract. *CASST™ herbicide (*Alternaria cassiae*) has been shown to be an effective biological control agent for sicklepod (*Cassia obtusifolia *L.), coffee senna (*Cassia occidentalis *L.) and showy crotalaria (*Crotalaria spectabilis *Roth). Current research has shown the potential of this mycoherbicide for use both alone and integrated with other herbicides as an effective commercial control measure for these troublesome weeds.*

Key words: pathogenic *Alternaria,* biocontrol, sicklepod, coffee senna, showy crotalaria, commercial preparation, bioherbicide

Introduction

Mycogen Corporation is developing CASST™ herbicide for the selective control of sicklepod and coffee senna in peanuts and soybeans. This herbicide consists of the indigenous fungus *Alternaria cassiae* Jurair and Kahn (Jurair and Kahn, 1960; Simmons, 1982), which has been patented as a mycoherbicide (Walker, 1983). Although the fungus was originally discovered in 1960 (Jurair and Kahn, 1960), it was not until 1981 that it was isolated from diseased sicklepod seedlings and shown to have potential as a biocontrol agent (Walker, 1982).

The efficacy of *Alternaria cassiae* as a biocontrol agent for sicklepod was demonstrated in 1982-83 in multi-state field trials (Charudattan et al., 1986). In these tests *A. cassiae* was shown to be superior to toxaphene (chlorinated camphene, 67-69 percent chlorine) for sicklepod control. Although toxaphene was reported as efficacious for sicklepod (Sherman et al., 1983; Oliver et al., 1974), its primary use was insect control; its use as a pesticide was cancelled after December 31, 1986 (Anonymous, 1982). Because of the cooperative efforts of numerous scientists in both public and private sectors, an alternative herbicide, *Alternaria cassiae*, was available for development as a selective biocontrol agent for sicklepod control.

Host weeds

The hosts of *Alternaria cassiae* are sicklepod, coffee senna and showy crotalaria (Walker, 1982). Showy crotalaria was originally cultivated in the United States as an erosion control crop, a green manure crop, or a forage. Unfortunately, seed of this species contains alkaloids which are toxic to cattle (Duke, 1983; Hughes et al., 1969). Showy crotalaria is considered to be a serious problem in Florida forests and rangelands and is increasing in soybean fields of Alabama and Mississippi (Charudattan, 1987).

Coffee senna has medicinal properties and is used for such purposes in certain tropical regions (Duke, 1983). It is cited as a weed of increasing economic importance in both Alabama and Georgia (Anonymous, 1986). It has been listed as one of the ten most troublesome weeds in Alabama cotton as well as in both Alabama and Georgia in soybean/special oil crops (Anonymous, 1980; Anonymous, 1983; Anonymous, 1986). Seed cotton yield reductions of 38 percent or greater were reported when cotton competed with coffee senna for the entire season (Higgins et al., 1985). Similarly, 35 percent seed yield reductions were reported when soybeans competed with coffee senna for the entire season (Teem, 1977).

Sicklepod, a non-nodulating legume, is the most troublesome of the three weedy hosts of *A. cassiae* (Anonymous, 1980; Anonymous, 1983; Anonymous, 1986; Buchanan and Hauser, 1980). In 1971 it was reported that it reduced seed cotton yields by 10 to 40 percent compared to weed-free yields (Buchanan and Burns, 1971). Similarly, sicklepod has been shown to reduce soybean yields as much as 35 percent dependent on soil and edaphic factors (Thurlow and Buchanan, 1972). Although the peanut plant is a very competitive crop, yields of this species also have been shown to be reduced in the presence of sicklepod plants (Hauser et al., 1975; Buchanan et al., 1976).

Sicklepod is probably a greater weed problem compared to coffee senna because of anthracnose on coffee senna (Teem et al., 1980; Gudauskas et al., 1977). Both sicklepod and coffee senna have hard seed coats and require mechanical or acid seed scarification for germination to occur (Teem et al., 1980). This contributes to the periodicity of germination which is observed under field conditions following mechanical disturbance of soil or occurrence of summer rain showers. The establishment of sicklepod and coffee senna as troublesome weed species is increased further

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by their germination over a wide temperature range from 15 to 36 C and emergence from soil depths up to 12.7 cm (Teem et al., 1980).

Recent studies have shown that both chlorimuron {2-[[[[4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino] sulfonyl] benzoic acid} and imazaquin {2-[4,5-dihydro-4-methyl-4-(1-methyl ethyl)-5-oxo-1H-imidazol-2-yl]-3-quinolinecarboxylic acid} can provide acceptable chemical alternatives to toxaphene for the control of sicklepod in soybeans (Edmund and York, 1987). Integration of various chemical herbicide treatments, including preemergence and postemergence applications with appropriate crop rotations and cropping management systems, provides an economical method of weed control in soybeans (Bridges and Walker, 1985, 1987).

The availability of alternatives to toxaphene in peanuts is more limited since the use of dinoseb [2-(1-methylpropyl)-4,6-dinitrophenol] and dinoseb-containing products was suspended October 7, 1986, by the Environmental Protection Agency. Dinoseb and dinoseb-containing products were used extensively for control of sicklepod and other weeds at the ground cracking stage of peanut growth. The mycoherbicide *Alternaria cassiae* provides a safe, efficacious alternative to toxaphene and dinoseb for sicklepod and coffee senna control in peanuts.

CASST™ herbicide

Biology

The active ingredient of CASST™ herbicide is the *A. cassiae* spore, which is produced by a modification of the method originally described by Walker and Riley (1982). The demonstration of *A. cassiae* host specificity for sicklepod, coffee senna and showy crotalaria concomitant to the resistance of peanut, soybean, corn (*Zea mays* L.), cotton and 26 other crop and weed species to the pathogen led to development of *A. cassiae* for controlling sicklepod (Walker, 1982).

The importance of free moisture for the infection process and subsequent efficacy of mycoherbicides is axiomatic. Because spores are live propagules, moisture is required for their germination on and infection of susceptible hosts. Initial studies showed that slight sicklepod infection occurred after a 2-hour dew period, and significant dry weight and plant number reductions occurred after a 4-hour dew period (Walker and Riley, 1982). However, an 8-hour dew period was required for 95 to 100 percent reductions in plant number and dry weight.

Dew period temperature also influences the efficacy of *A. cassiae* on sicklepod. Temperature, however, is not as significant as free moisture to mycoherbicide performance. A temperature range of 20 to 30 C was shown to be optimum for sicklepod plant kill (Walker and Riley, 1982). A reduction in product efficacy was observed at 10 C or 35 C. At 35 C, spore germination does not appear to be affected. Appressorial formation, however, is severely inhibited (Bannon, unpublished data). Current data indicate that spore viability and virulence are maintained indefinitely when spores are stored in a desiccator at 5 C. Research is in progress to determine other methodologies which would be suited for spore storage over a broader temperature range.

Inoculum concentration influences the efficacy of *A. cassiae* on sicklepod seedlings. Initial studies conducted under greenhouse conditions showed that maximum injury of the seedlings occurred when inoculum concentrations were $\geq 5 \times 10^4$ conidia/ml (Walker and Riley, 1982). Dependent upon inoculum density this is equivalent to a 1.1 to 2.2 kg/ha rate if seedlings are sprayed to runoff ($\sim$1, 871 L/ha). A 1.1 kg/ha rate of *A. cassiae* conidia has been shown to be most efficacious for controlling sicklepod under field conditions (Bannon and Walker, 1987; Bannon et al., 1988).

Light is a very important environmental variable which has not been widely studied in the fungal infection process (Goodman et al., 1986). In 1987 it was shown that light intensity was directly correlated with phytotoxicity of *A. cassiae* on sicklepod (Bannon and Hudson, 1988). The inoculation of sicklepod with *A. cassiae* at night in the same study resulted in a decline in efficacy, further supporting the concept of importance of light to mycoherbicide activity.

Integrated approaches

Enhancement of pathogen virulence by chemical modification of host physiology was cited in 1982 (Templeton 1982). Enhanced efficacy of specific bioherbicides with chemical herbicides has been covered in a recent review (Templeton et al., 1986). Quimby (1983 reported that glyphosate [N-(phosphonomethyl) glycine] applied at a rate which caused only negligible (0-5 percent) injury to soybeans enhanced the efficacy of *A. cassiae* on sicklepod. Recently, it has been reported that *A. cassiae* efficacy on sicklepod is significantly enhanced by lactofen [(±)-2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(trifluoromethyl phenoxy]-2-nitrobenzoate] and 2,4-DB [4-(2,4-chlorophenoxy) butyric acid (Bannon et al., 1988). In this same study gibberellic acid combined with mixtures of 2,4-DB and *A. cassiae* was effective in alleviating environmental stresses such as reduced dew period, on the pathogen. Although this study must be confirmed under field conditions in 198 reduction of *A. cassiae* dew period requirements through exogenous applications of a naturally occurring plant hormone is an encouraging result.

Formulation

CASST™ herbicide is presently a 10 percent active ingredient spore preparation. In 1986, spores of *A. cassiae* were determined to be hydrophobic, and it was demonstrated that emulsified crop oils were superior to non-ionic surfactants for application of the spores (Bannon and Walker, 1987). Since some crop oils and emulsifiers are known to be fungitoxic agents (Forsyth, 1964), the proper selection of these ingredients is crucial to successful application of *A. cassiae* spores. Additionally, the ratio of emulsifier to oil is critical to flow properties of the spore through screens, no

zles and subsequent deposition on the host leaf surface. Because of the influence of the adjuvant system on *A. cassiae* efficacy, a research program on special surfactants for *A. cassiae* is in progress. Recent research (Quimby et al., 1988) has shown that an invert emulsion can decrease the dew requirement of *A. cassiae* in controlling sicklepod.

Production

Production of commercial mycoherbicides has recently been reviewed (Churchill, 1982; Stowell et al., 1988). Currently, spores of *A. cassiae* are produced by a modification of the method described by Walker and Riley (1982). Research programs are in progress on more efficient methods of inoculum production.

Shelf life

Current research indicates that desiccated spores of *A. cassiae* will remain viable and virulent indefinitely when stored at 5 C. Desiccated spore storage above or below 5 C has been observed to cause changes in virulence and viability. Other standard procedures, such as lyophilization, soil cultures, etc., are also used as techniques to preserve this mycoherbicide. Because of the hydrophobic nature of the spore, storage in various oils is also an acceptable technique. Both the type of oil and additives such as emulsifiers may influence spore viability/virulence over time. Thus, the suitability of these materials as carrier systems for commercial formulations remains under long-term investigation.

Summary

The efficacy of *A. cassiae* for controlling sicklepod, coffee senna and showy crotalaria has been well documented (Boyette, 1988). Research continues to show that this mycoherbicide can be integrated with existing practices for weed control in important crops such as peanuts and soybeans. Integration of *A. cassiae* with chemical herbicides or plant growth regulators has shown synergistic weed control responses. The potential for replacing the dew period requirement through both innovative formulation techniques and use of naturally occurring plant growth regulators has been demonstrated. The future of biological weed control agents, including *A. cassiae*, appears bright as horizons for alternative weed control agents continue to expand.

References

1. Anonymous. 1980. Weed survey. Res. Rep. South. Weed Sci. Soc. 33:165-197
2. Anonymous. 1982. Notice of intent to cancel registrations and denial of applications for registration of pesticide products containing toxaphene. U.S. Federal Register, November 29, 1982. U.S. Government Printing Office, Washington, DC.
3. Anonymous. 1983. Weed survey. Res. Rep. South. Weed Sci. Soc. 36:148-184.
4. Anonymous. 1986. Weed survey. Res. Rep. South. Weed Sci. Soc. 39:136-158.
5. Bannon, J. S., and H. L. Walker. 1987. Influence of non-ionic surfactants and non-phytotoxic crop oils on control of sicklepod by *Alternaria cassiae*. Proc. South. Weed Sci. Soc. 40:288.
6. Bannon, J. S., and R. A. Hudson. 1988. The effect of application timing and lighting intensity on efficacy of CASST™ herbicide (*Alternaria cassiae*) on sicklepod (*Cassia obtusifolia* L.). WSSA Abst. 28:143.
7. Bannon, J. S., R. A. Hudson, L. Stowell, and J. Glatzhofer. 1988. Combinations of herbicides/plant growth regulators with CASST™ herbicide (*Alternaria cassiae*). Proc. South. Weed Sci. Soc. 41:268.
8. Boyette, C. D. 1988. Biocontrol of three leguminous weed species with *Alternaria cassiae*. Weed Technology 2:414-417.
9. Bridges, D. C., and R. H. Walker. 1985. Influence of weed management and cropping systems on sicklepod seed in the soil. Weed Sci. 33:800-804.
10. Bridges, D. C., and R. H. Walker. 1987. Economics of sicklepod (*Cassia obtusifolia*) management. Weed Sci. 35:594-598.
11. Buchanan, G. A., and E. R. Burns. 1971. Weed competition in cotton. I. Sicklepod and tall morningglory. Weed Sci. 19:576-579.
12. Buchanan, G. A., and E. W. Hauser. 1980. Influence of row spacing on competitiveness and yield of peanuts (*Arachis hypogaea*). Weed Sci. 28:401-409.
13. Buchanan, G. A., E. W. Hauser, W. J. Ethredge, and S. R. Cecil. 1976. Competition of Florida beggarweed and sicklepod with peanuts. II. Effects of cultivation, weeds, and SADH. Weed Sci. 24:29-39.
14. Charudattan, R. 1987. Biological control of showy crotalaria (*Crotalaria spectabilis* Roth.) with two fungal pathogens. Proc. South. Weed Sci. Soc. 40:289.
15. Charudattan, R., H. L. Walker, C. D. Boyette, W. H. Ridings, D. O. TeBeest, C. G. Van Dyke, and A. D. Worsham (eds.). 1986. Evaluation of *Alternaria cassiae* as a mycoherbicide for sicklepod (*Cassia obtusifolia*) in regional tests. Southern Cooperative Series Bull. 317, Southern Regional Research Project S-136, Dept. of Research Information, Alabama Agric. Expt. Sta., Auburn Univ., Alabama 36849.
16. Churchill, B. W. 1982. Mass production of microorganisms for biological control. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens. John Wiley and Sons, New York, New York. pp. 139-156.
17. Duke, J. A. 1983. Handbook of legumes of world economic importance. Plenum Press, New York, New York. 345 pp.
18. Edmund, R. M., Jr., and A. C. York. 1987. Factors affecting postemergence control of sicklepod (*Cassia obtusifolia*) with imazaquin and DPX-F6025: spray volume, growth stage, and soil-applied alachlor and vernolate. Weed Sci. 35:216-223.
19. Forsyth, F. R. 1964. Surfactants as fungicides. Can. J. Bot. 42:1335-1347.
20. Goodman, R. N., K. Zoltan, and K. R. Wood. 1986. The Biochemistry and Physiology of Plant Disease. University of Missouri Press, Columbia, Missouri. 433 pp.
21. Gudauskas, R. T., D. H. Teem, and G. Morgan-Jones. 1977. Anthracnose of *Cassia occidentalis* caused by *Colletotrichum dematium* f. *truncata*. Plant Dis. Rep. 61:468-470.
22. Hauser, E. W., G. A. Buchanan, and W. J. Ethredge. 1975. Competition of Florida beggarweed and sicklepod with peanuts. I. Weed-free maintenance and weed competition. Weed Sci. 23:368-372.
23. Higgins, J. M., R. H. Walker, and T. Whitwell. 1985. Coffee senna (*Cassia occidentalis*) competition with cotton (*Gossypium hirsutum*). Weed Sci. 34:52-56.
24. Hughes, H. D., M. E. Heath, and D. S. Metcalfe. 1969. Forages, the science of grassland agriculture. The Iowa State University Press, Ames, Iowa. 707 pp.
25. Jurair, A. M. M., and A. Khan. 1960. A new species of *Alternaria* on *Cassia holosericea* Fresen. Pakistan J. Sci. Ind. Res. 3:71-72.
26. Oliver, L. R., W. M. Lambert, and A. R. James. 1974. Control of leguminous weeds in soybeans with post-emergence applied herbicides. Proc. S. Weed Sci. Soc. 31:94.
27. Quimby, P. C., Jr. 1983. Applying *Alternaria cassiae* to sicklepod. Proc. South. Weed Sci. Soc. 36:473.
28. Quimby, P. C., Jr., F. E. Fulghum, C. D. Boyette, and W. J. Connick, Jr. 1988. An invert emulsion replaces dew in biocontrol of sicklepod--a preliminary study. In D. A. Houde and G. B. Beestman (eds.). Pesticide Formulations and Application Systems: Eighth Volume, ASTM STP 980. American Society of Testing and Materials, Philadelphia, Pennsylvania.
29. Sherman, M. E., L. Thompson, Jr., and R. E. Wilkinson. 1983. Sicklepod (*Cassia obtusifolia*) management in soybeans (*Glycine max*). Weed Sci. 31:622-627.
30. Simmons, E. G. 1982. *Alternaria* themes and variations (7-10). Mycotaxon 14:17-43.
31. Stowell, L., K. Nette, B. Heath, and R. Shutter. 1988. Fermentation alternatives for commercial production of a mycoherbicide. Abst. Soc. Ind. Microbiol. p. 13.
32. Teem, D. H. 1977. Factors affecting the growth and distribution of sicklepod (*Cassia obtusifolia* L.) and coffee senna (*Cassia occidentalis* L.). Ph.D dissertation, Auburn University, Alabama. 144 pp.

33. Teem, D. H., C. S. Hoveland, and G. A. Buchanan. 1980. Sicklepod (*Cassia obtusifolia*) and coffee senna (*Cassia occidentalis*): geographic distribution, germination and emergence. Weed Sci. 28:68-71.
34. Templeton, G. E. 1982. Status of weed control with plant pathogens. In R. Charudattan and H. L. Walker (eds.). Biological Control of Weeds with Plant Pathogens. John Wiley & Sons, New York, New York. pp. 29-44.
35. Templeton, G. E., R. J. Smith, Jr., and D. O. TeBeest. 1986. Progress and potential of weed control with mycoherbicides. Reviews of Weed Science 2:1-14.
36. Thurlow, D. L., and G. A. Buchanan. 1972. Competition of sicklepod with soybeans. Weed Sci. 20:379-384.
37. Walker, H. L. 1982. Seedling blight of sicklepod caused by *Alternaria cassiae*. Plant Disease 66:426-428.
38. Walker, H. L. 1983. Control of sicklepod showy crotalaria, and coffee senna with a fungal pathogen. U.S. Patent 4,390,360.
39. Walker, H. L., and J. A. Riley. 1982. Evaluation of *Alternaria cassiae* for the biocontro of sicklepod (*Cassia obtusifolia*). Weed Sci 30:651-654.

UPCOMING EVENTS

February 28. Sustainable Farming Systems: Needs and Opportunities, a symposium sponsored by the Institute for Alternative Agriculture, in Washington, DC. Symposium goals include an examination of the characteristics of low-input, integrated farms and those policy barriers that limit the broader adoption of these diversified systems. Contact the Institute for Alternative Agriculture, 9200 Edmonston Road, Suite 117, Greenbelt, MD 20770, (301) 441-8777.

March 8-10. The Promise of Low-Input Agriculture, sponsored by the Soil and Water Conservation Society, in Omaha, Nebraska. The conference will explore ways to incorporate profitable, environmentally sound agricultural production techniques with conventional agricultural systems. Public policy and educational aspects of low-input farming will be addressed, as will impediments to adoption of sustainable farming techniques and the risks of adoption. The Institute for Alternative Agriculture is a co-sponsor. Contact Alan Epps, SWCS, 7515 Northeast Ankeny Road, Ankeny, IA 50021-9764, (515) 289-2331.

March 16-17. National Conference on Organic/Sustainable Agriculture, sponsored by the Center for Science in the Public Interest and others, in Washington, DC. Panels will address standards for organic foods, marketing, economics, and policy issues in organic farming. The Institute for Alternative Agriculture is a co-sponsor. Contact the CSPI, 1501 - 16th Street, NW, Washington, DC 20036.

March 27-30 and April 4-6. International Vedalia Symposia on Biological Control, in Riverside, California (March) and McAllen, Texas (April). The meeting commemorates a century of successful biological controls which began with the importation of the Vedalia Beetle from Australia in 1888-89 to control Cottony Cushion Scale in California citrus. The symposia will provide overviews of the role of biological controls. Contact the International Symposia on Biological Control, Department of Entomology, University of California, Riverside, CA 92521.

April 23-26. Making Nonpoint Pollution Control Programs Work: The Water Quality Act of 1987, sponsored by the National Association of Conservation Districts and the National Association of State Conservation Administrators, in St. Louis, Missouri. Contact William Horvath, NACD North Central Office, 1052 Main Street, Stevens Point, WI 54481, (715) 341-1022.

May 3-5. Shitake Mushrooms: A National Symposium and Trade Show, in St. Paul, Minnesota. The symposium will provide information on shitake production and marketing as well as identifying needs in the industry. The meeting is sponsored by the Center for Alternative Crops and Products, College of Natural Resources, University of Minnesota, the Minnesota Extension Service, and others. Contact Extension Special Programs, University of Minnesota, 405 Coffey Hall, 1420 Eckles Avenue, St. Paul, MN 55108.

May 11-12. National Research Conference on Pesticides in Terrestrial and Aquatic Environments, sponsored by the Virginia Water Resources Research Center and the Virginia Polytechnic Institute and State University, in Richmond, Virginia. Topics will include pesticide monitoring, environmental effects and risk assessment, pesticide control management, and case studies. Contact the Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, 617 North Main Street, Blacksburg, VA 24060-3397.

July 22-25. International Herb Growers and Marketers' 4th Annual Conference and Trade Show, in San Jose, California. Topics cover production, marketing, and business aspects of herb growing. Contact the International Herb Growers and Marketers Association, P.O. Box 281, Silver Springs, PA 17575.

July 30-August 2. The Soil and Water Conservation Society Annual Meeting, in Edmonton, Alberta. The program will focus on ways to achieve coordination and teamwork in natural resource conservation. Contact Alan Epps, SWCS, 7515 Northeast Ankeny Road, Ankeny, IA 50021-9764.

Use of biological control measures in the intensive management of insect pests in New Jersey

James H. Lashomb, William Metterhouse, and Robert Chianese

Abstract. *The U.S. public is expressing strong preference for the use of biological control methods in the management of U.S. agricultural, forest, and rangeland insect pests. This follows from a widespread understanding among citizens that synthetic insecticides have potentially harmful side effects on humans and that they are spreading increasingly as pollutants in the environment. Major recent increases in the number of pesticide-resistant insect species also put pressure on the agricultural community toward adoption of alternative non-agchemical plant and animal protection strategies. Movement in the direction of such alternatives has been facilitated by the fact that in the last two decades much progress has been made in Integrated Pest Management (IPM) through an improved understanding of the interactions of pests with their hosts. In that time period, many advances have been made in describing and predicting insect movement, seasonal cycles, and the effects of secondary plant compounds on insect reproduction. Simultaneously, much has been learned about the behavior, physiology, and population dynamics of insect parasitoids, i.e. parasites on insect pests. In the 1990's and subsequently, Biological Control Intensive Pest Management (BCIPM) will require continuing research to attain needed advancement in knowledge of growth and development of host plants, population dynamics of pests and parasitoids, and ecology of secondary pests that may interfere with implementation of BCIPM programs. Extension and research personnel will then be increasingly able to devise useful control methods for pests within selected cropping systems. We describe here examples to illustrate present and potential future use of BCIPM in different practical plant systems in New Jersey.*

Key words: integrated pest management, insect movement, seasonal cycles, insect reproduction, parasitoids, forests, ornamentals, fruit trees, forage and field crops, vegetables, sod

Introduction

As the public's knowledge of BCIPM methods increases, so also is there an increase in the acceptability of such methods and in the scope of their practical implementation. Pest situations to be targeted must be ones in which the IPM technology is most appropriate. Certain background facts and principles need to be understood. The stability of the habitat in which host plants are grown determines the types of pest that occur and which natural enemies will be effective in control (Southwood, 1977). The final use and cash required per year to produce the crop determine the time and place when and where BCIPM can be successfully used. High cash value plantings have to be intensively protected so as to at least recoup the required investment, while crops with low cash value leave more margin for error.

Figure 1 shows the nature of some of the common cropping systems in New Jersey in relation to the expected lifetime of the crop and the cash input required for that period. Successes in biological control have been for many reasons numerous in forest systems. The forest habitat is very stable (Hall and Ehler, 1979). It also commonly includes many plant species, so it is structurally complex. Relevant also is the fact that with the exception of beetles in southern pine, most major forest pests have only one generation per year. In addition, the value per acre of forest land is low, so that the use of insecticides against most forest pests is not economically practical. For these reasons, the common practices in forests are the use of natural enemies in conservation and enhancement measures and importation and establishment.

Present practices and future possibilities

Ornamentals

Plant populations in ornamental plantings in yards, parks, and roadsides are less complex than those in woodlands but complex enough to support a diverse group of natural enemies that keeps many pests in check. Once a plant species is grown as an ornamental, however, i.e. away from the habitat from which it evolved, herbivores of marginal impact in the original habitat, such as scales, mealybugs, aphids, and mites,

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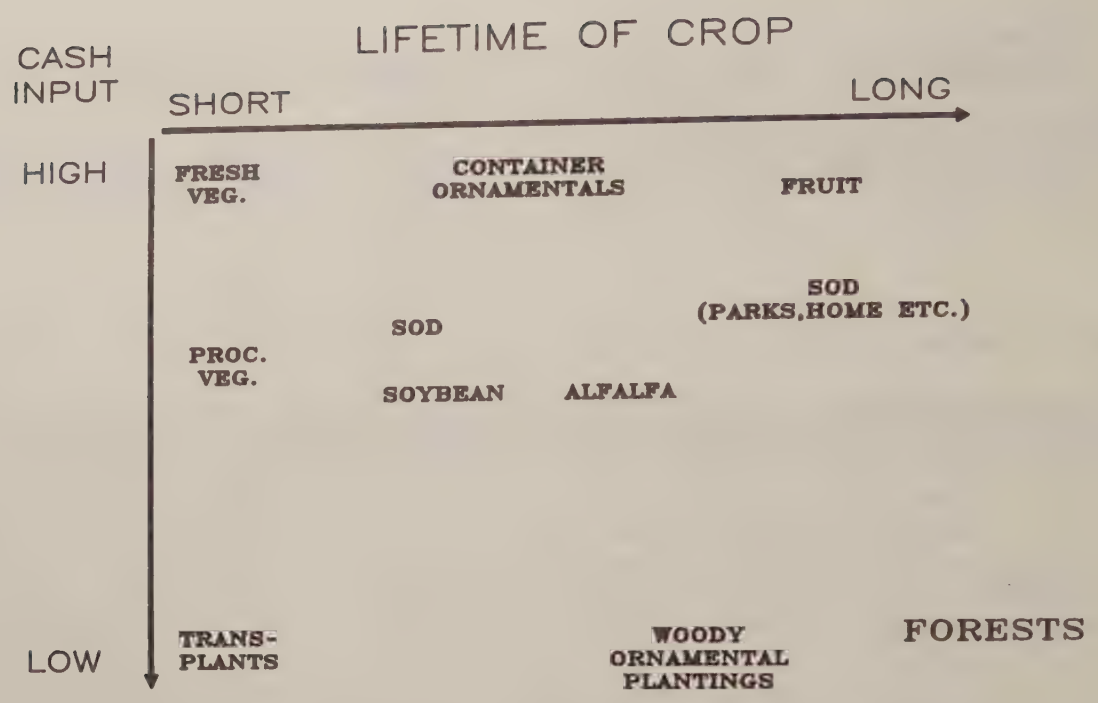

Figure 1. Production matrix showing lifetime of selected crops occurring in New Jersey relative to annual cash value of each.

frequently become a problem. The hemlock-attacking wooly adelgid (*Adelges tsugae*) in recent years has, for example, become a serious problem on older plantings of ornamental hemlock.

Possibilities for enhancement of endemic natural enemies and for importing and establishing new beneficials are being explored. Euonymus scale, *Unaspis euonmyi*, is an important ornamental pest of euonymus, holly, and Pachysandra, all popular plants in suburban home settings and parks. An establishment program involving USDA-ARS personnel in cooperation with the New Jersey Department of Agriculture in the use of two new lady beetle predators has been started. Once the natural enemies are established, an active distribution program will begin in order to ensure that they are dispersed throughout the state.

Fruit crops

Fruit trees are of high ornamental value in the yard and high cash value in the orchard. Many pests are fruit feeders. With peaches, the trunk and branches must be protected from borers. Feeding by these insects may cause large branches to break, severely impairing ornamental or crop value. Insecticides probably will remain the chief management tool for protecting the fruit and branches, but BCIPM can be used to target specific pests such as mites (see article by Hoy in this issue). We are actively investigating the utility of a small coccinellid beetle (*Stethorus punctum*) in an augmentative strategy aimed at suppressing the European red mite *Panonychus ulmi* in apples. Presently that mite is resistant to nearly all labelled miticides in New Jersey, so if a "window" in the pesticide application regime can be found, it may prove possible to reduce the mite to sub-economic levels (Hull and Beers, 1985).

Forage and field crops

Alfalfa and soybeans are highly suitable for BCIPM methods because of their relatively low value per hectare. With these crops, BCIPM is very effective in New Jersey. The alfalfa weevil (*Hypera postica*) became the most serious pest of alfalfa following an outbreak in the eastern U.S. in the 1950's. All acreage had to be sprayed several times per year to kill the insect. Intensive exploration of the weevil's native habitat yielded four parasitoids. They were imported, established, and are now preventing damaging populations from developing in New Jersey and other eastern states in the classical pattern of biological control. Since then, another classical BCIPM case has occurred with the alfalfa blotch leaf miner *Agromyza frontella*. Although this fly posed less of a problem than the weevil, two introduced parasites and some endemics have reduced its importance to that of a non-pest.

In soybean, the Mexican bean beetle (*Epilachna varivestis*) became troublesome in the early 1970's. In response, the New Jersey Department of Agriculture Beneficial Insects Laboratory began an annual inoculative release program for use of *Pediobius foveolatus* against the beetle larvae by the end of the decade, following the guidelines of Stevens et al. (1975). This eulophid wasp is an exotic gregarious larval parasitoid imported from India. Producers participate by growing small snapbean nurse plots on the edge of soybean fields. Snapbeans are more attractive to the adult beetles

than soybean. The wasps are released in low numbers in the nurse plots, where they parasitize Mexican bean beetle larvae. When the wasp progeny emerge, they disperse into the soybean field to attack more bean beetle larvae. This program is pursued on a regional basis in New Jersey, and it appears that the regional populations of the beetle have been reduced since its initiation. A newly introduced chalcid wasp, *Uga menoni*, a larval parasitoid of the beetle, has been released in several sites in the state and is now being evaluated for establishment and effectiveness.

Vegetables

The use of BCIPM in field-grown fresh vegetables faces many problems because the crop must be pest-free and devoid of marks when sold at auction. Brokers will prevent shipment of thousands of dollars of produce if they find live insects or their damage. Likewise, customers at roadside stands will search for the best-appearing produce and discard marked or damaged fruit or vegetables. As is shown in Figure 1, the life cycle of most vegetables is relatively short, lessening the time that natural enemies can find and use to kill their host, and the cash inputs to produce and protect the crop are higher annually than with other crops.

The fresh vegetable cropping system used by New Jersey growers is very complicated. They grow an average of 30 different crops in one season on an average farm size of about 20 hectares. Figure 2 shows some of the complexity that each farmer must face. Typically, they will grow many short-season crops that require a single harvest, usually with 1-3 crops that require multiple harvests. I have termed the long-season crops the "Keystone crops" because it appears that the farmers elect to make a predictable profit on these and use the twenty-odd others to improve their risks. That is, among all those short-season crops, some of them yield high prices in any one year, while some others may be plowed in before harvest because the market price is too low. Otherwise, growers may opt to reduce losses by selling their produce wholesale. In this case, though, they have cultured their crop for retail at a plant protection cost higher than needed for selling the produce wholesale. Marketing vagaries, coupled with a 9-10 month season of continual planting, culturing, harvesting, replanting, and marketing result in a very delicate aggregate cropping system in which the margin of error is small.

In certain cases, BCIPM may work in such cropping systems. Eggplant (*Solanum melongena*) is a very important crop in New Jersey; the state is the major national supplier in the summer. It qualifies as a "Keystone crop" for it can yield profits of up to $8,000 per hectare from 11-12 pickings if the pests can be adequately managed. Figure 3 shows the kinds of pests which occur on an annual basis in eggplant, also their natural enemies. The two spotted spider mite (*Tetranichus urticae*), potato leaf hopper (*Empoasca fabae*), and eggplant flea beetle (*Epitrix fuscula*) are occasional pests and are easily managed. The Colorado potato beetle (*Leptinotarsa decemlineata*) (CPB) is a devastating pest, for without direct and frequent intervention the crop will be destroyed each season. In the past 10-15 years, each eggplant grower in New Jersey has either lost his whole crop or important portions of it several times. The fear this insect has engendered in farmers results in 12-15 sprays per year, just for the beetle. This intense schedule has resulted in an insect that is highly resistant to nearly all labelled insecticides (Forgash, 1981). Commonly, a new insecticide is marketed for the beetle and within a couple of years resistance appears, spray dosages are increased, and mixtures of other insecticides are used. During those years, large-scale crop failures occur.

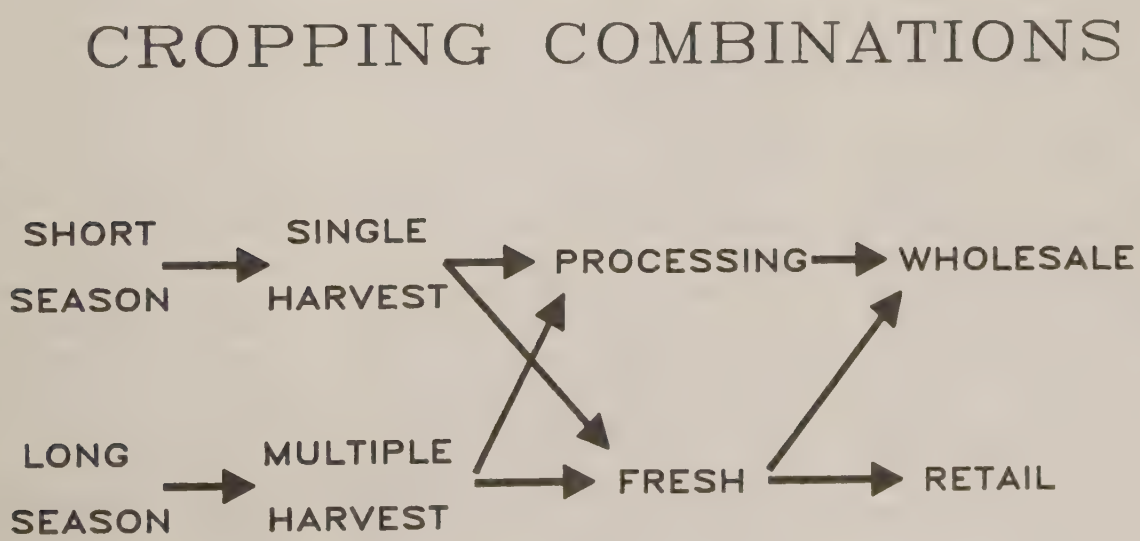

Figure 2. Complexity pathways that an average New Jersey vegetable farmer faces when growing a mean of 30 crops per season.

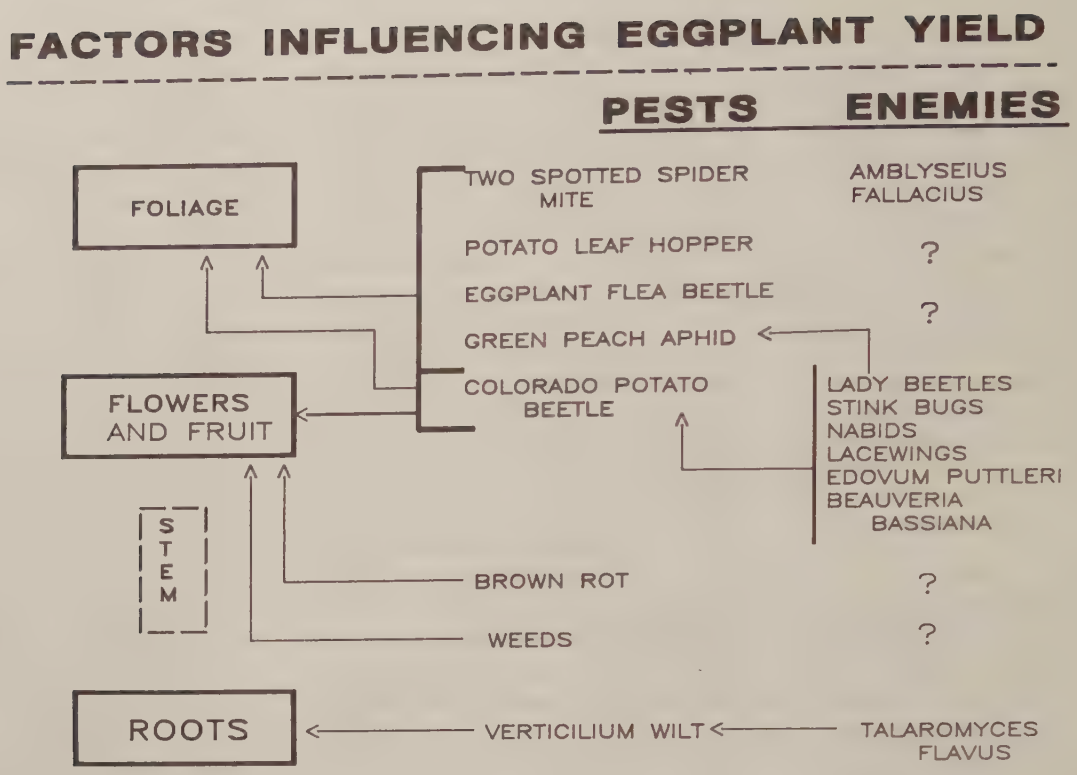

Figure 3. A conceptual model of pests attacking egg plant and natural enemies attacking those pests.

This treadmill drives up production costs and greatly increases grower anxiety.

The great difficulties presented by resistance result in a situation in which even the most reluctant farmers must adopt alternative methods for protecting yield. In the case of the Colorado potato beetle, conventional IPM techniques are either ineffective or nonexistent. For instance, endemic natural enemies have been shown to be effective only at low host densities (Harcourt, 1971) because they respond too slowly to numerical increases of the beetle. Also, lack of control by endemics is probably a result in part of the prolonged (60-day) emergence of overwintering adult beetles, the enormous fecundity of the beetle (Lashomb et al., 1987a), and short durational stability of the crop. There are differences in cultivar susceptibility to the beetle (Jannson et al., 1987), but there are no resistant cultivars, and no plant breeding for resistance is under way. The fungal pathogen *Beauveria bassiana* has been tested against the beetle in potato both as foliar and soil treatments, but neither method showed long-term promise. Lashomb and Ng (1984) showed that the cultural method of rotation is effective in delaying buildup of CPB in potato and, when used, saves 2-3 sprays in that crop. This method is already used in eggplant, for if the growers do not rotate, the plants will die from Verticillum wilt (*Verticillium* sp.). This disease causes serious rotational problems for growers because spores can survive up to five years after being planted to a host crop and this disease has many hosts besides eggplant.

Edovum puttleri (EP), a small parasitic wasp of *Leptinotarsa* eggs, shows great promise for suppressing beetle populations in eggplant. The wasp was imported from Colombia, South America, after which it cleared quarantine with flying colors. Puttler and Long (1983) showed conclusively that the wasp would not survive on beneficials and, in fact, would only survive on beetles from the genus *Leptinotarsa*. Unfortunately, the wasp will not survive temperate winters, so it must be released each year as an inoculum. Several factors increase its potential for widescale use as an annual inoculative release in eggplant. First and foremost is the incredibly high control costs to growers of between $300 and $600/acre for a highly insecticide-resistant insect. Other important factors include small on-farm plantings (average size of 2 hectares); it is the only host crop on the farm; concentrated acreage in the state (making long travel time between farms unnecessary); partial insecticide tolerance of the wasp to rotenone and full compatibility to *Bacillus thuringiensis* San Diego, and seasonality of control costs.

Important biological factors contribute to the potential success of this BCIPM technique, i.e. favorable plant architecture, optimal activity temperatures for the wasp, complete exploitation of the eggmass by *Edovum*, reduced fecundity of the beetle in eggplant. The architecture of eggplant and *S. sapanacium*, the species from which EP was initially collected, are very similar in

that they both have broad leaves and an indeterminate growth habit. Since eggplant can only be grown after frost, mean daily temperatures that the wasps encounter are similar to those in their native habitat (Lashomb et al., 1987b). Once a female finds an eggmass, she will kill 95 percent of all eggs (Lashomb, 1987a, b; Jannson et al., 1987). Fecundity of the beetle is reduced in eggplant relative to potato (Jannson and Lashomb, unpublished), so a slower population buildup of the beetle occurs in eggplant. Additionally, predation by stinkbugs on CPB larvae increases if the crop is not sprayed. We are presently testing the hypothesis that the EP release program has reduced population growth of the beetle to the point that the inversely density-dependent predators play an important role in protecting the crop. Coccinellid predators exhibit an important influence, for they build up quickly in the absence of sprays to the point that no economic populations of green peach aphids *Myzus persicae* (GPA) occur. Thus, an indirect effect of the wasp release program is saving the two sprays growers commonly apply for controlling aphids.

Our methods for the wasp release program and subsequent management of the crop are evolving. Figure 4 shows data from four fields where wasps have been released. To ensure stand establishment, we recommend after transplanting that the plants be kept pest-free until they have six new leaves. Without chemical intervention, the newly emerged overwintering adult beetles will kill new transplants by chewing the eggplant stems at the base of the plant, thus making extensive replanting necessary. In addition, leaf feeding by CPB adults and larvae before substantial vegetative development will seriously retard plant growth. During this period, the fields are colonized by the eggplant flea beetle. Prolonged adult feeding definitely reduces photosynthetic area, but in most cases the CPB sprays protect the plant from flea beetle attack. Marketing of eggplant is very competitive. The pricing curve is "U"-shaped, with high early and late-season prices, so any retardation of early yield can put the farmer at a competitive disadvantage.

Once the plants have six new leaves, we begin an eight-week period in which the wasps are released twice weekly for a total of 10,000/ha for the season. Wasps are conditioned on the host in the mass rearing laboratory for several days so they are in peak egglaying condition at release (Lashomb et al., 1987b; Jannson et al., 1987). During the season, we monitor the fields twice weekly for all CPB life stages, GPA, two spotted spider mites, eggplant flea beetle, potato leafhopper, diseases, and new problems. Jannson et al. (1987) and the data in Figure 4 show that our release strategy is very effective. We use a value of six large larvae/plant as a threshold for spraying (Cotty and Lashomb, 1981).

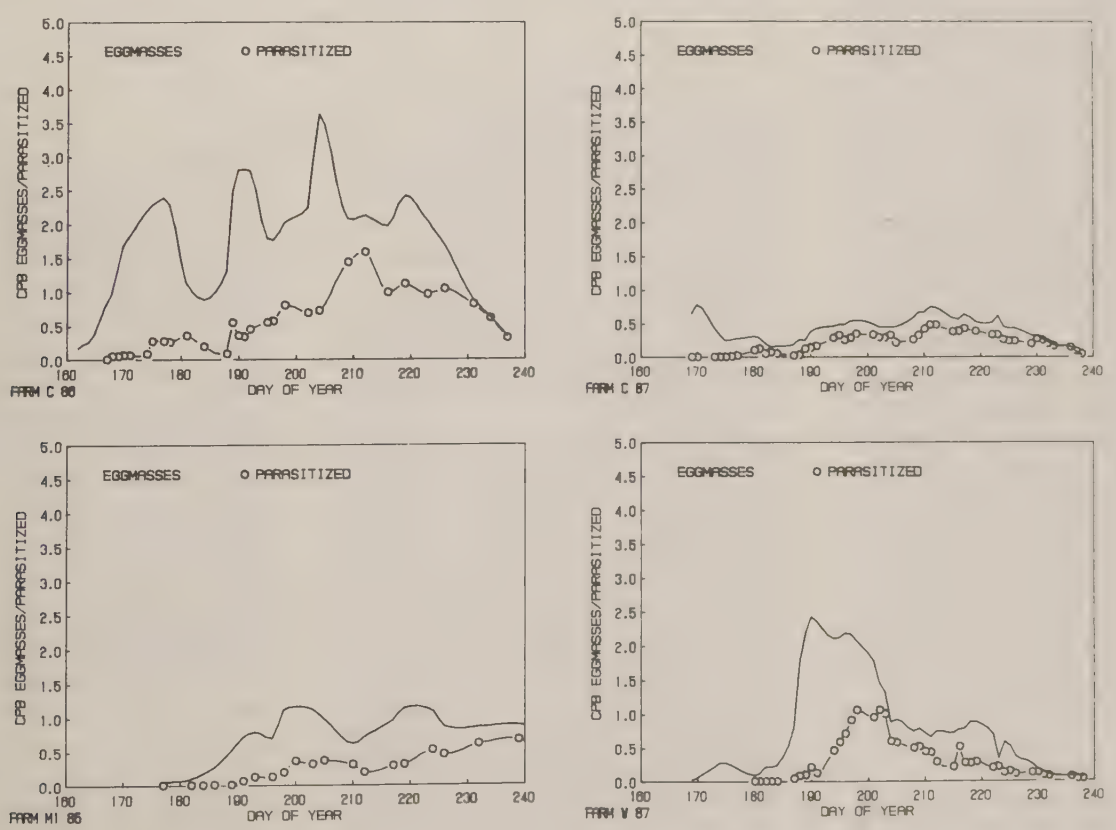

Figure 4. Incidence curves from four farms of Colorado potato beetle eggs in egg plant and eggs parasitized by *Edovum puttleri.*

Farm MI 85 and W 87 required 0 and two sprays for larvae after release began. Following those two sprays, no insecticide was required for the season. Fields C 86 and C 87 represent eggplant on the same farm over a two-year period. Field C 86 required two sprays following release and C 87 required one. In the absence of sprays or when widescale resistance occurs, second generation beetles are usually 2-3 times higher in number than first generation beetles. In these four fields and all others where we have conducted this program, second generation populations are lower than first. Also, the data from C 86 and C 87 showed a sharp decrease in beetles from one year to the next. If this program becomes adopted by farmers on a regional basis, it is possible that we can lower annual average abundance of the beetle with our BCIPM program.

We are presently reviewing our data to test cost effectiveness of this BCIPM technique. If it is cost effective, we will demonstrate that this program lowers production costs by: avoiding further resistance development of the beetle; greatly reducing insecticide usage; eliminating sprays applied for GPA; increasing opportunities for marketing by releasing the farmer from mixing, transit time to field and actual spray time; and potentially reducing the on-farm/regional abundance of the beetle. Since the acreage is highly concentrated in the state, program delivery costs will be reasonable. Also, because the growers have only 1-2 plant hosts on the farm, reinvasion problems of Colorado potato beetle from other crops does not occur. We recognize the long-term liabilities of rearing the wasp annually, but with development of an artificial diet for CPB and other EP rearing advances, these difficulties can be minimized. In addition, with the increasing costs of insecticides and the lurking specter of increasingly insecticide-resistant beetles, BCIPM in eggplant seems realistic.

Sod

Commercial production of sod has increased sharply in New Jersey. Further, as a result of a suburban building boom, there has been a large increase in acreage of parks, golf courses, and lawns. These habitats are prime targets for invasion by the Japanese beetle (*Popilla japonica*) and other turf pests. Since nearly the whole commercial sod ecosystem is removed from the farm each year at harvest, BCIPM in that system is not realistic because the numbers of natural enemies cannot increase. In the residential and park setting, substantial mortality occurs during each year's growing season from milky spore disease, parasitic nematodes, and wasps. In fact, New Jersey is the locality where these natural enemies were either found or established decades ago. This was the first biological control program in the state, which in turn spawned a six-decade commitment by the New Jersey Department of Agriculture to biological control.

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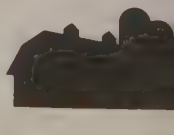
References

1. Anon. 1988. New York Times Editorial. November 11, 1988.
2. Cotty, S., and J. H. Lashomb. 1981. Vegetative growth and yield response of eggplant to varying first generation Colorado potato beetle densities. Journ. N. Y. Entomol. Soc. pp. 220-228.
3. Forgash, A. 1981. Insecticide resistance of the Colorado potato beetle *Leptinotarsa decemlineata* Say. In J. Lashomb and R. Casagrande (eds.). Advances in Potato Pest Management, Ross Publishing Co., Stroundsburg, Pennsylvania. pp. 34-46.
4. Hall, R. W., and L. E. Ehler. 1979. Rate of establishment of natural enemies in classical biological control. Bull. Entomol. of Amer. pp. 280-282.
5. Harcourt, D. G. 1971. Population dynamics of *Leptinotarsa decemlineata* (Say) in Eastern Ontario. III: Major population processes. Canad. Entomol. pp. 1049-1061.
6. Hoy, M., and D. C. Herzog. 1985. Biological Control in Agricultural IPM Systems. Academic Press. 589 pp.
7. Hull, L., and E. H. Beers. 1985. Ecological selectivity: modifying chemical control practices to preserve natural enemies. In M. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, New York, New York. pp. 103-121.
8. Jannson, R. K., J. Lashomb, E. Groden, and R. Bullock. 1987. Parasitism of *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae) by *Edovum puttleri* (Hymenoptera: Eulophidae) in different cultivars of eggplant. Entomophaga. pp. 503-510.
9. Lashomb, J., and Y. S. Ng. 1984. Colonization by Colorado potato beetles, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae), in rotated and nonrotated fields. Environ. Entomol. pp. 1352-1356.
10. Lashomb, J., Y. S. Ng, R. Jannson, and R. Bullock. 1987a. *Edovum puttleri* (Hymenoptera: Eulophidae), an egg parasitoid of Colorado potato beetle (Coleoptera: Chrysomelidae) development and parasitism in eggplant. Environ. Entomol. pp. 65-68.
11. Lashomb, J., D Krainacker, R. Jannson, Y. S. Ng, and R. Chianese. 1987b. Parasitism of *Leptinotarsa decemlineata* eggs by *Edovum puttleri* (Hymenoptera: Eulophidae): effects of host age, parasitoid age and temperature. Canad. Entomol. pp. 75-82.
12. Puttler, B., and S. H. Long. 1983. Host specificity tests of an egg parasite *Edovum puttleri* (Hymenoptera: Eulophidae) of the Colorado potato beetle, *Leptinotarsa decemlineata* (Coleoptera: Chrysomelidae). Proc. Entomol. Soc. Wash. pp. 384-387.
13. Southwood, T. R. E. 1977. Habitat, the template for ecological strategies? Journ. Anim. Ecol. 46:337-365.
14. Stevens, L., A. L. Steinhauer, and J. Coulson. 1975. Suppression of Mexican bean beetle on soybeans with annual inoculative released on *Pediobius foveolatus*. Environ. Entomol. pp. 947-952.
15. Waage, J., and D. Greathead. 1986. Insect Parasitoids. Academic Press. 389 pp.

Winning with Water, a report from the non-profit research group Inform, shows that the use of gypsum-blocks to monitor soil wetness can help cut water use by up to 58 percent. Electrodes in the blocks, which are buried in crop root zones, are connected to insulated wires that lead to the field surface where meters can read water levels. In 20 field tests, water reductions resulting from use of the monitors averaged 20 to 40 percent. Copies of the report are available from Inform, 381 Park Avenue South, New York, NY 10016.



Pheromones: Their potential role in control of agricultural insect pests

Philipp Kirsch

Abstract. *Serious side effects from the conventional use of traditional chemical pesticides for routine arthropod pest management have prompted the investigation and development of alternate strategies for the minimization of pest damage. Insect sex pheromones have been proposed as a potential group of alternative control agents for over twenty years. The possible uses of these substances for insect control are discussed and factors influencing their development for pest management are presented. The scientific research and commercial development of oriental fruit moth mating disruption is presented as a case study for the commercialization of this approach. Advantages and limitations of pheromone-based control tactics are presented. Mating disruption technology is starting to find its place in a number of diverse cropping situations. The use of pheromones for pest control promises to be an important component of the ongoing challenge to develop alternatives that may help to solve major environmental and human health problems associated with chemical pesticide use in agriculture.*

Key words: chemical pesticides, toxicity, insect sex pheromone, mating disruption, monitoring, oriental fruit moth, codling moth, pear, peach, pest management

Introduction

The widespread post-World War II use of synthetic chemicals for control of pests in agricultural systems has freed farmers from much of the worry and complexity of managing arthropod pests without pesticides but has been accompanied by serious costs. These costs include pesticide poisoning through direct human exposure, indirect human exposure through pesticide residues in food and water and widespread environmental contamination. Further, many chemicals are no longer effective in controlling their target insects as a result of increased pest tolerance and resistance. Seven insect and mite pests were resistant to pesticides in 1938; by 1984 this figure had climbed to 447 (Georghiou, 1986). Resistance often leads to an increase in the frequency and dosage rate of subsequent pesticide applications, and this "pesticide treadmill" can ultimately lead to yield reduction instead of yield enhancement or yield stabilization. Postel (1988) observes that farmers and pesticide producers are now locked into a race with the rapid evolution of crop pests.

Pesticides often kill natural parasites and predators of insect pests (Hassan et al., 1987) and in this way any potential for natural biological control is reduced. Further, removal of these biological agents leads to outbreaks of secondary pests and increases the need for additional pesticide applications. For example, in 1981, Gut et al. estimated that ca $60/ha/yr of insecticide applications for the control of codling moth *(Cydia pomonella)* on pears *(Pyrus communis)* in Oregon and Washington resulted in the outlay of an additional ca $450/ha/yr for the control of pear psylla *(Psylla pyricola)* and two-spotted spider mite *(Tetranychus urticae)*. In pear orchards untreated with insecticides, psylla (Westigard, 1973; Westigard and Moffit, 1984) and mites (Hoyt et al., 1978; Zwick and Fields, 1978) are both kept at non-damaging levels by biological agents.

The number of new chemicals coming onto the marketplace is decreasing, in part, due to increasing complexity of chemical structure and synthesis, and also due to a stricter regulatory climate. It now costs industry between $20-45 million to bring a new pesticide onto the market, compared with about $1.2 million in 1956 (Postel, 1988). Regulatory bodies governing pesticide registration currently require submission of extensive product data, including a mandatory battery of expensive toxicology tests, for review prior to approval of product registration. Although pheromones also require registration prior to commercial use, registration requirements for pheromones are minimal. Pending and proposed legislation in the United States, including stiff product reregistration requirements, the Environmental Protection Agency's (EPA) Pesticide Label requirements for Preventing Poisoning of Endangered Species, and the EPA's Agrichemicals in Groundwater Strategy (released February 25, 1988) could force the cost of introduction of new agricultural pesticides even higher.

Public chemophobia is forcing a rapid reevaluation of current pest control strategies. In late 1986, voters in California overwhelmingly approved Proposition 65, a referendum that shifts at least some responsibility for chemical safety to the chemical and agricultural industry. This bill has prompted at least two large farming corporations in California to adopt strategic plans that propose the elimination of all pesticides

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from their agricultural production practices over the next five years.

Clearly, there exists a need for the development and adoption of alternatives in pest management. Insect pest management is in a transition. Ten to twenty years ago, there was an almost total reliance on the prophylactic use of synthetic chemicals. In the last ten to fifteen years, much research has focussed on the development of integrated pest management (IPM) systems (eg. Frisbie and Adkisson, 1985), which address the intelligent selection and use of pest control strategies that will ensure favorable economic, ecological and sociological consequences (Metcalf and Luckman, 1975, p. 4). This does not mean a total ban on synthetic pesticides, but requires the careful integration of these materials as part of a holistic program that considers the entire ecosystem.

Through the implementation of IPM strategies, the number of insecticide and miticide applications required for pest control has been markedly reduced in a number of situations (eg. Headley and Hoy, 1986; Madsen, 1981; Madsen and Carty, 1977; Wall, 1984; Zalom et al., 1984, 1987). However, alternatives to pesticides are not readily available for the control of most insect and mite pests and the further development of IPM will depend, in part, on the development of more environmentally acceptable pest control products (Mueller, 1988; Wearing, 1988). If there is to be any further reduction in the use of insecticides, research efforts into the development of alternative systems will need to be expanded. In 1987, the U.S. Committee on Science, Engineering, and Public Policy included a report on 'Biological Control in Managed Ecosystems' in their annual Research Briefings. This report concludes that "biological control can and should become the primary method used in the United States to ensure the health and productivity of important plant and animal species.... The development of biological control as the foundation of pest control in the United States is the most important challenge (faced) in making safe and efficient use of our managed ecosystems" (Cook et al., 1987).

This paper discusses the role of insect pheromones as one of the components of biological control and IPM and the potential for their use in agricultural pest management.

Background on insect pheromones

The presence of insect pheromones has been alluded to since the late middle ages. As early as 1609, Charles Butler wrote the following in his treatise *The Feminine Monarchie*: "When you are stung, or anyone in the company, yea though a Bee have strike but your clothes, specially in hot weather, you have best be packing as fast as you can: for the other bees smelling the ranke flavour of the poison cast out with the sting will come about you as fast as the haile" (in Davidson,1985).

Pheromones have been described as substances produced by insects that have a specific effect on members of their own species (Bartell, 1977). They were originally defined as "substances which are secreted to the outside by an individual and received by a second individual of the same species, in which they release a specific reaction, for example, a definite behaviour or a developmental process" (Karlson and Luscher, 1959). These chemical signals are secreted in minute quantities by many insects for communication with others of their kind. They can evoke many responses including aggregation, alarm, trail-following, defense, feeding, and reproduction.

In the last three decades, the study of pheromones has developed into an important section within the discipline of chemical ecology. The cumulative number of published lepidopterous (moths and butterflies) sex pheromones has risen from one in 1959 (Butenandt et al., 1959) to over 1600 in 1987 (Arn et al., 1986). Pheromones have now been identified for many of the major agricultural pest species from the order Lepidoptera. A number of them have also been identified for pest species from the orders Coleoptera (beetles) (Bestman and Vostrowsky, 1988), Hymenoptera (ants, bees and wasps) and Isoptera (termites) (Wheeler and Duffield, 1988), Diptera (flies) (Fletcher and Bellas, 1988a), and Blattodea (cockroaches) and Hemiptera (true bugs) (Fletcher and Bellas, 1988b).

Applications of insect pheromones in pest management

Practical applications of pheromone in pest management can fit into the following categories:

a. Trapping for detection in monitoring and survey.

b. Monitoring levels of insecticide resistance using pheromones as attractants.

c. Luring insects to areas treated with insecticides.

d. Luring insects to areas treated with pathogens, which are then spread by the infected individuals to the rest of the population.

e. Mass-trapping for population suppression.

f. Disrupting communication within the insect population by permeation of the atmosphere with pheromone. When using sex pheromones, mating disruption should result in population suppression.

Monitoring and survey

Insect sex pheromones have been developed into tools for pest detection in pest management since the early 1970's (eg. Riedl et al., undated; Wall, 1984). Following identification, they are synthesized and then formulated as lures or various substrates. Attractant traps baited with lures emitting very low amounts of the specific insect sex pheromone, are used for detecting the first arrivals of an immigrant population and/or the initial adults of each generation of a resident population.

In quarantine situations, detection records are used to estimate presence/absence of potential pest populations and indicate new areas of infestation (Kennedy, 1981). For agricultural pests pheromone traps are generally used as monitoring tools. When pheromone trap catches exceed a certain threshold level the potential risk for economic damage warrants a protective pesticide application. Timing of this pesticide application can be predicted (eg Rice et al. 1984

with some knowledge of the relationship between the date of this threshold catch and subsequent oviposition and developmental rate of the pest. This optimization of pesticide applications has lead to reductions in insecticide usage of up to 50 percent (Madsen, 1981; Madsen and Carty, 1977; Hagley et al., 1977; Wall, 1984; Antle and Park, 1986) through the abandonment of a prophylactic spray-on-schedule control approach and the adoption of precision timed applications.

Monitoring resistance

Pheromone traps can also be effectively used to monitor levels of insecticide resistance in the population (Riedl et al., 1985; Haynes et al., 1986, 1987). This method incorporates varying dosages of insecticides into the trapping mechanism (sticky liner or water bath) and hence requires little or no handling of insects and no need for topical dosage of insecticides. Results are rapid, and due to the ease of use, this technique should be valuable to growers and consultants making decisions regarding pesticide application. In a New Zealand fruit growing district, pheromones were used to lure male insects from different habitats to capture in insect nets, and the regions of insecticide resistance were then identified by topically testing the collected male insects for levels of insecticide resistance (Suckling et al., 1985).

Mass trapping

In a control strategy based on mass trapping, pheromones attempt to remove a segment of the population and hence reduce the success of subsequent generations. In the case of lepidoptera, traps baited with female sex pheromone remove males and attempt to reduce the mating success of females. Trials with this strategy in stored products, forestry and agricultural crops have met with mixed results. In stored products, the technique may be effective when low insect populations prevail (Burkholder and Ma, 1985). Pheromones may be used as agents to attract pests to sites baited with spores of pathogens (Shapas et al., 1977). In forestry, mass-trapping used in combination with host baiting and subsequent removal of infested trees has been relatively effective as a means of controlling and reducing infestations of some bark beetle species including *Dendroctonus brevicomis*, the western pine beetle (Bestman and Vostrowsky, 1988). Outstanding results were achieved with mass-trapping in the control of the spruce engraver beetle, *Ips typographus* in Norway by using its aggregation pheromone. The 1976 pretreatment annual loss of three million pine trees due to beetle attack was reduced to a level of 200,000 in 1982 (Lie, 1984).

Sternlicht (1982, 1986) presents results demonstrating successful control of the citrus flower moth *(Prays citri)* in lemons *(Citrus limonia)* in Israel using mass-trapping. Over a three-year period, flower infestation in plots treated with 120 pheromone traps/ha was reduced by levels of 38 to 50 percent when compared to plots treated with the conventional insecticide program. Madsen et al. (1976) were successful in controlling codling moth through male removal by installation of 10 pheromone traps per ha in an isolated orchard with a low codling moth population.

Teich et al. (1985) report that mass-trapping on thousands of hectares against the pest, Egyptian cotton leafworm *(Spodoptera littoralis)*, for four consecutive years in Israel resulted in a 20 to 45 percent reduction in insecticide treatments. Mass-trapping of this pest is now part of the integrated management strategy for cotton produced in Israel. The use of pheromone traps for detecting and suppressing the cotton boll weevil, *Anthonomus grandis*, is a major component of an area-wide eradication project in the southeastern United States (Legget et al., 1988) that has resulted in a 50 to 70 percent reduction in the use of insecticides (Booth, 1988). This USDA Boll Weevil Eradication Program has virtually eliminated this pest from North and South Carolina and Georgia.

Few other attempts at using this approach in control of agricultural pests have met with success and mass-trapping with sex pheromones has not been effective in reducing lepidopterous damage to commercially acceptable levels in other crops (Campion and Nesbitt, 1982; Madsen and Carty, 1979; Roelofs et al., 1976; Taschenberg et al., 1974).

Increasing pest contact with toxicants

When combined with pesticides, pheromones can be used to enhance contact between the target pest and a toxicant. This approach has been marketed commercially for a number of pests including artichoke plume moth *(Platyptilia carduidactyla)*, pink bollworm *(Pectinophera gossypiella)*, tomato pinworm *(Kefferia lycopersicella)* and *Tetranychus* spp. phytophagous mites. For the lepidopterous species, insecticides are employed in the adhesives used to adhere pheromone dispensers to the foliage of the crop. Males contacting such sources receive lethal or sublethal doses of the insecticide (Haynes and Baker, 1985), termed "attracticide" and are temporarily or permanently removed from the reproductive population (Miller et al., 1986). Many cotton growers, employing this tactic for the control of pink bollworm, maintain that this "attracticide" technique allows them to reduce the absolute amount of pheromone applied while maintaining the same level of pest control as with standard rates of pheromone (Baker, 1985).

Mating disruption - Background

Many female insects release a sex pheromone into the atmosphere to attract the male for the purpose of mating. When male insects of the same species detect the pheromone, they then orient themselves upwind in the direction of the pheromone source. In this manner, male insects are able to locate fertile and sexually mature females. Mating disruption explores the concept of using synthetic formulations of sex pheromones to disrupt this orientation of male insects to their mates. If successful, the reduced number of matings within the population should lead to suppression of the population over subsequent generations.

Use of this control technique has been proposed for well over 25 years (Beroza,

1960; Wright, 1964a,b, 1965) following recognition that the olfactory guidance system of flying insects is a complex one, and therefore potentially vulnerable to disruption. Nevertheless, by 1984, the widespread application of synthetic sex pheromones, attractants and even inhibitors, in attempts to suppress population levels by interfering with the pests' premating behavior, had produced only two examples of consistent success, oriental fruit moth *(Grapholita molesta)* in peaches in Australia (Rothschild, 1975; Vickers et al., 1985) and pink bollworm in North America (Doane and Brooks, 1981; Henneberry et al., 1981; Baker, 1985; Baker et al., in press) and Egypt (Jutsum et al., 1983; McVeigh et al., 1983; Critchley et al., 1983, 1985). Commercially acceptable control had also been demonstrated in Japan for tea tortrix *(Homona magnanima)* and smaller tea tortrix *(Adoxophyes* sp.*)* (Anonymous, 1986) and for artichoke plume moth in California (Haworth, et al., 1982).

Since then, commercially acceptable levels of control, using pheromones for mating disruption, have been demonstrated for oriental fruit moth in California (Weakley et al., 1987; Rice and Kirsch, in press), grape berry moth *(Endopiza viteana)* in New York state (Dennehy et al., in press), second generation European grape berry moth *(Eupoecilia ambiguella)* in Germany (Englert, 1987; Neumann, 1987), tomato pinworm in California (Jimenez, 1988), lesser peachtree borer *(Synanthedon pictipes)* and peachtree borer *(Synanthedon exitiosa)* in the southeastern United States (Snow, in press), codling moth in Switzerland (Charmillot, 1987; Mani et al., 1984, 1987) and the bagworm moth *(Thyridopteryx ephemeraeformis)* in Maryland (Klun et al., 1986).

Factors influencing development of mating disruption control strategies

Economics

Kydonieus and Beroza (1982) state that unfavorable economics are the major deterrent to the expanded use of pheromones. Prior to any marketing and cash return, a high capital output is required for completion of the following steps to take place:

a. development of synthetic pathways for economically viable commercial production of high-quality pheromone active ingredient.

b. development of a controlled release formulation that can be patented.

c. approval for experimental use permits to allow field testing.

d. commencement of field testing to demonstrate to growers that insect control is maintained at economically acceptable levels. This can be quite expensive as trials generally need to cover large areas.

e. completion of toxicological tests required by environmental protection agencies.

f. registration of the product by environmental protection agencies.

g. design and manufacture of the equipment needed for manufacture of the pheromone dispensers.

Once the product has been proven in the field and registered, additional high technical service requirements are necessary due to the newness of the concept.

When the requirement for this high initial capital outlay is considered along with the following factors of a more technical nature, it is not difficult to understand why commercial expansion of the use of pheromones as control agents has been limited. These materials have a limited market due to their species-specific nature, and often the expected rate of return on the initial investment will not justify the initial investment (Siddall and Olsen, 1976). As Baker (1985) points out, once mating disruption reaches commercialization, the technology is buffeted by forces that have nothing to do with its potential usefulness or efficacy.

Baker (1985) argues that the final test of mating disruption technologies is in the marketplace, buffeted by forces that have nothing to do with product efficacy. Products may be successful in doing what they were designed to do but may be dropped commercially because they do not make enough profit. Chemical companies often choose to sell pesticides that have broad applications (Booth, 1988; Mueller, 1988), and i seems that the initial commercializatio of pheromone products may be under taken by small entrepreneurial compa nies. Government support of such organizations could help speed the introduction of these new alternatives.

Kydonieus and Beroza (1982) suggest that government grants, awarded to such companies, would give great impetus to the development of these alternative systems. Such grants could initially target three areas: a) the development of commercially competitive synthetic pathways for pheromone active ingredient; b) the development of controlled release systems; and c) the performance of large-scale field trials to demonstrate efficacy against economically important pest species.

For example, where one component was initially demonstrated to be attractive for male codling moth (Roelofs et al., 1971), recent studies indicate that a more complete, multiple component, synthetic blend should enhance behavioral activity (Arn et al., 1985; Bartell and Bellas, 1981; Einhorn et al., 1984, 1986). Development in this understanding of the chemistry of sex pheromones has been directly linked to spectacular advancements in the analytical techniques of organic chemistry, combined with increasingly objective and effective behavioral and electrophysiological bioassays (Klun, 1985).

Pheromone synthesis and cost. Due to the expense involved in the early synthesis of insect sex pheromones, there was only limited material available for widespread broadcasting in mating disruption attempts. As a result, most early trials were conducted in very small plots. In the early 1970's, mating disruption trials aimed at control of oriental fruit moth demonstrated control comparable to that achieved with conventional insecticide programs (Rothschild, 1975). However, the prohibitive cost of the pheromone at that time, about $22,000/kilo, prevented any further commercialization (Davidson, 1985).

In recent years, reduction in cost of the active ingredient was a major factor in the development and implementation of mating disruption as an economically viable alternative to conventional insec

ticides used in oriental fruit moth control (Davidson, 1985; Vickers et al., 1985; Weakley et al., 1987). Similarly, a reduction in the cost of active ingredient has led to the development and implementation of a number of promising mating disruption systems in grapes *(Vitis* spp.*)* (Dennehy et al., in press), peaches *(Prunus persica)* (Snow, in press) and tomatoes *(Lycopersicum esculentum)* (Jimenez, 1988), and the commercial introduction of a high dose system for pink bollworm in cotton *(Gossypium* spp.*)* (Baker et al., in press).

Efficacy of pheromone formulations. Inadequate dispensing technology is another factor contributing to the lack of commercial success resulting from most early attempts at mating disruption. A number of dispensing systems have been developed, including microfibres, trilaminate-flakes, microencapsulated formulations, trilaminate tapes and polyethylene tubes. Specifications for release rate of component ratios, method of application, field persistency or longevity, utilization of formulated pheromone and product cost vary among dispensing systems (Critchley et al., 1985; Rothschild, 1979, 1982).

Differences in dispenser performance contribute significantly to product efficacy in disruption attempts, and the choice of which controlled release technology to use in large-scale field experiments should be based upon a careful pre-treatment analysis of dispenser performance. Only then can research presume that dispensing technology was adequate in trials where attempts at mating disruption have failed. Further, monitoring dispenser performance under field conditions is just as important as evaluating behavior of the target pest.

The nature of release technology used in attempts at disruption will largely determine the mechanisms underlying mating disruption (Bartell, 1982). If false trail following is the most likely mechanism (Sanders, 1986), it becomes extremely important to ensure that pheromone dispensing systems are creating the most attractive pheromone plumes possible, plumes which are at least competitive with virgin females. Understanding the influence that different physical characteristics of the crop environment and different meteorological conditions have upon the production of these plumes should lead to the design of more effective systems.

Following comparison of five different dispensing systems, polyethylene tubes were demonstrated to be the dispensing system of choice for oriental fruit moth under Australian field conditions (Rothschild, 1979). Recent studies have demonstrated the efficacy of these dispensers in controlling peachtree borer and lesser peachtree borer (Snow, in press) and grape berry moth (Dennehy et al., in press). Hollow fibres, laminate-flakes and microencapsulated formulations, as well as polyethylene ropes, have all been demonstrated as effective dispensing systems for the pink bollworm (Baker et al., in press; Critchley et al., 1985). Supplementary insecticides to augment control of late season pink bollworm infestation are required for all disruption formulations in North America.

Adequate understanding of pest behavior. In most cases, virtually nothing is known about the behavior of target pests under natural conditions, let alone such behavior when these insects are presented with the stimuli of synthetic pheromone sources in the field. Male response to individual pheromone sources and plumes has been studied quite extensively for a few insect pests in the laboratory and to some extent in the field (reviewed by Baker, 1985; Sanders, 1986; Wall and Perry, 1987). Response of males to multiple pheromone sources and pheromone clouds has also been evaluated (Baker, 1985; Bartel, 1982; Sanders, 1982a,b, 1986).

A number of mechanisms for the disruption of pheromone-mediated male behavior have been proposed (Bartell, 1982; Cardé, 1981; Charlton and Cardé, 1981; Rothschild, 1981; Sanders, 1982a,b, 1986). Sanders (1982a,b, 1986) concludes that the mechanism most likely to be involved in disrupting orientation of the male insect to the female is the creation of false trails of synthetic pheromone in the crop environment. The numerous false trails presented to male insects in environments containing large numbers of synthetic pheromone dispensers would compete with the natural pheromone trails released by female insects. This then leads to a reduction in mate-finding by male insects.

Studies on the female response to synthetic sex pheromone concentrations are very limited (Palaniswamy and Seabrook, 1985). Greater activity of female moths in the presence of pheromone may contribute to disruption, since moving moths cannot copulate. It may also indicate that high concentrations of pheromone may cause dispersal, with profound implications in spatial population dynamics. An understanding of the interactions among locomotion, calling, oviposition and dispersal of female moths is as essential to understanding disruption as is male behavior (Sanders, 1987), and future research on mechanisms of mating disruption should place greater emphasis on this facet of the insects' behavior.

Studies on the impact that delayed mating has on the reproductive potential of female moth pests suggest that significant reductions in female fecundity and fertility follow such delays (Barrer, 1976; Kiritani and Kanoh, 1984; Rothschild, 1981; Swaby et al., 1987). As the objective of disruption is to interfere with mating, it is reasonable to expect that the potential for success of experimental attempts in disruption is enhanced by the possible female response to delayed mating. In species where delayed mating has negative effects on the reproductive potential of the female, one could expect that pheromone-induced mating delays will have deleterious effects on female fecundity and hence contribute to control of the target pest.

It is remarkable that very little is known about the mating behavior of most common moth pests in the field when it is considered that the objective of disruption is to interfere with mating. One reason for the lack of field behavioral studies is that many of these pests are nocturnal; nevertheless, this handicap has been overcome in some situations (Dunkelblum et al., 1987; Lingren, 1983). Field behavioral studies that lead to a greater understanding of underlying mechanisms involved in mating and hence in mating disruption should also lead to the potential design of more robust systems of pest control using pheromones (Bartell, 1982).

Adequate understanding of insect movement and the crop environment. In comprehensive disruption trials extending over a full field season, it has often been stated that the results were inconclusive because of probable immigration of mated females from adjacent areas. A major problem in field experiments, this is often accentuated by the small scale of most trials (Rothschild, 1981).

Prior to the establishment of mating disruption trials in the field, it is important to evaluate the potential influence that surrounding crops may have. Extended host searching by gravid females can often be overcome in the trial design by spraying an insecticide border around the pheromone-treated plot. Border treatments of this nature have been effective in mating disruption trials on oriental fruit moth and codling moth (unpublished data).

Charmillot (1987) reports that when mating disruption breaks down it is in the borders of the crop. He recommends that disruption for codling moth be attempted only in orchards larger than 1-3 ha. For fruit infesting insects, the harvest dates of the trial crop should be compared with those of the surrounding fields, as gravid females may move towards a maturing crop from one that has already been harvested. On the other hand, many of the limitations imposed by insect movement can be overcome by conducting mating disruption trials on a large scale.

Understanding of the behavior of pheromone molecules. Although many researchers have attempted to measure the behavior of volatiles (plumes) released from point sources (e.g. Wall and Perry, 1982, 1987; Stanley et al., 1985, and references therein), little research on mating disruption in the field has investigated the pattern of atmospheric dispersion of pheromone chemicals during the trial. Wind movement within crop canopies has been studied (Shaw, 1982), yet this discipline is rarely applied to mating disruption experiments. Little information has been generated on how these chemicals, following release from different dispensing systems, are spatially and temporally distributed within the environment. Field research of this nature has been limited by sampling and analysis techniques that are not sensitive enough to detect aerial concentrations of pheromone applied at the low rates adequate for disruption experiments (Taylor, 1982).

Physical characteristics of the crop and meteorological conditions (Wall, 1984) probably have the most effect on this vapor dispersal. Physical characteristics are likely to affect the movement of air and hence the dispersal of vapors. One could expect differences between a cotton crop and a vineyard or between a young peach orchard (2.5 m high) and a mature walnut *(Jugians* spp.*)* orchard (15 m high). An understanding of these differences could lead to placement of dispensers within the crop at points that would maximize dispersion of the pheromone throughout the canopy. Meteorological conditions predominating when the insect is active in the field would also have an important effect on vapor dispersal. Understanding the influence of these conditions, e.g. wind speed, temperature and air turbulence, could lead to the design of controlled release systems with optimum performance for certain environments.

Wall (1984) suggests that it is imperative to pay due attention to both the physical characteristics of the environment that the insect is passing through in its search for the pheromone source and the type of meteorological conditions that predominate at the time. If insects use different communication strategies in different ecological/meteorological situations, then it would be very useful to identify these strategies prior to the commencement of experimental control programs. The direction of development of future pheromone-based control strategies could be profoundly influenced by a better understanding of the relationship between insect behavior and these abiotic factors.

Mating disruption - A case study

Oriental fruit moth - Background

Oriental fruit moth is a serious pest of peaches throughout the world (Hill, 1975, p. 257). In all major peach-growing regions, control has been dependen on insecticides. This pesticide usage ha created major problems with secondary pests, two-spotted spider mite, and gree peach aphid *(Myzus persicae)*, throug the virtual elimination of natural pre dators (Field, 1976).

The first component of oriental fruit moth pheromone, Z-8-dodecenyl acetate, was described nineteen years ago (Roelofs et al., 1969). Since then, several authors have shown that the female releases lesser amounts of additional components (for review see Baker and Cardé, 1979). Baker and Cardé (1979) demonstrated that at least three of these additional components elicit some behavioral response from the male insect. Baker (1985) reviews recent studies on these behavioral responses. Mating disruption experiments with oriental fruit moth have been undertaken by Rothschild (1975, 1979), Gentry et al. (1975, 1980), Cardé et al. (1977), and Charlton and Cardé (1981).

Oriental fruit moth - Australian development of mating disruption

Following identification of the primary component of OFM pheromone by Roelofs et al. (1969), research commenced to determine whether control o oriental fruit moth could be achieved by the release of sufficient quantities o pheromone into the insects' environmen to prevent or reduce sexual communication. In Australia, all of these trials were based on formulations of the single pheromone component identified in 1969, but fortunately two of the other behaviorally active components, E-8-dodecenyl acetate and dodecenol, were present as impurities in this active ingredient (Davidson, 1985).

Field experiments, mostly in commercial orchards, were undertaken to establish the minimum release rate o pheromone, the necessary number of release points, and the dispenser placement necessary to achieve commercially acceptable levels of control. Rothschild (1975) reported that the pest population in a pheromone-treated field could be suppressed to levels that were generally lower than those in insecticide-treated fields. He showed the necessity of treat

ing large areas to prevent immigration of mated females and concluded that the very high cost of the active ingredient prevented the technique from becoming economically competitive.

Problems also arose due to inefficient release rates of the dispenser at low temperatures and subsequent research concentrated on improving the dispenser. A number of methods of dispensing synthetic sex pheromone were compared and Rothschild (1979) concluded that polyethylene microcentrifuge tubes were the most suitable. Trials conducted in 1980-1982 (Vickers et al., 1985) assessed mating disruption in commercial orchards at a district level, that is, all potential sources of infestation were treated with pheromone to prevent immigration of mated females. These trials were very successful, leading to the conclusion that mating disruption was a viable alternative to conventional insecticide programs.

Pheromone for these trials was supplied by Shin Etsu Fine Chemicals, who developed a commercially available dispenser, the polyethylene tube, using the principles embodied in Rothschild's experimental dispenser. When loaded with oriental fruit moth pheromone, this dispenser maintains constant release rates for 90 days, even when exposed to high summer field temperatures. [This same dispenser has recently been formulated for mating disruption trials that have demonstrated control of grape berry moth (Dennehy et al., in press), lesser peachtree borer and peachtree borer (Snow, in press), pink bollworm (Baker et al., in press), and tomato pinworm (Jimenez et al., 1988)].

Oriental fruit moth - Commercialization of mating disruption in Australia

In 1982, upon completion of district level trials (Vickers et al., 1985), the following factors promoted the commercial implementation of mating disruption for this insect pest:

a. research, stretching over 10 years, demonstrating commercially acceptable levels of control,

b. a competitively priced pheromone source, and

c. a commercially available and reliable dispenser.

The dispenser was then commercialized by a company with a technical base in the demonstration and implementation of mating disruption.

Oriental fruit moth mating disruption has replaced conventional insecticides in over 25 percent of the Australian peach market, following registration in 1984. New South Wales Department of Agriculture surveys have found that the mating disruption approach has consistently yielded less than 1 percent fruit damage, compared to an industry average of 4.4-4.9 percent using insecticides (John Slack, New South Wales Department of Agriculture, 1985, 1986, personal communication). The Australian peach industry is starting to contemplate the possibility of wide-scale reduction of oriental fruit moth population levels using pheromones. Some industry leaders believe a regulatory stance should be adopted to encourage farmers in peach-growing districts to adopt an area-wide eradication strategy (John Slack, personal communication).

Oriental fruit moth - Commercialization of mating disruption in North America

Mating disruption trials in California were commenced cooperatively between the University of California and Biocontrol Ltd. in 1985. These trials evaluated mating disruption in five peach and nectarine orchards throughout the state. Pheromone trial orchards were paired with conventionally sprayed blocks at each location, and pheromone trap captures and bait traps were used to monitor population levels throughout the season. Fruit damage assessments at harvest indicated that levels of control achieved through mating disruption were equal to or better than those following the conventional insecticide program (Weakley et al., 1987). Control resulted in fruit damage levels, following pheromone application, that were consistently less than 0.05 percent (Table 1). Similar levels of control were achieved in trials conducted in 1986 (Table 2) and 1987 (Table 3) (Rice and Kirsch, in press).

These results lead to the conclusion

Table 1. 1985 Mating disruption trials for the control of oriental fruit moth in California peaches: Fruit damage from oriental fruit moth (OFM) and from other species.

		% Damage in treatments:	
Orchard	Pest	Pheromone	Insecticide
Sutter	OFM	0.10	0.33
	Other[1]	0.85	0.17
Yuba	OFM	0.00	0.00
	Other	2.65	0.00
Sanger	OFM	0.10	0.15
	Other	0.30	0.25
KAC	OFM	0.10	4.00
	Other	2.40	0.85
Mean[2]	OFM	0.08	1.12
	Other	1.55	0.32

[1] Includes peach twig borer, omnivorous leaf roller *(Platynota stultana)* and codling moth.
[2] Treatments not significantly different at the 0.05 level.

Table 2. 1986 Mating disruption trials for the control of oriental fruit moth in California orchards[1]: Fruit damage from oriental fruit moth (OFM) and from other species (adapted from Rice and Kirsch, in press)

		% Damage in treatments:			
Orchard	Pest	Pheromone[2]		Comparison[3]	
Parlier	OFM	14.2		59.3	(0)
Fld. 21	Other[4]	5.0		31.7	
Parlier	OFM	0.9		59.3	(0)
Fld. 24	Other	1.5		31.7	
Kingsburg	OFM	0.5		1.5	(0)
	Other	0.2		0.8	
Arvin	OFM	0.5		0.3	(1)
	Other	0.3	(1)	0.6	(1)
Reedley (Quince)	OFM	0.8		1.7	(4)
Livingston	OFM	0.9		0.0	(2)
	Other	3.6	(1)	0.2	
Escalon	OFM	0.4		0.0	(1)
	Other	1.9	(1)	0.2	
Lomo-1	OFM	0.3		1.2	(2)
	Other	0.1		0.0	
Lomo-2	OFM	0.3		1.2	(2)
	Other	0.0		0.0	
Yuba City	OFM	1.0	(1)	0.4	(4)
	Other	0.2		0.1	
Live Oak	OFM	0.1		0.5	(3)
	Other	0.5		0.1	

[1] Different cultivars of peach and nectarine and one quince treatment (Reedley).
[2] Number of insecticides applied for control of peach twig borer in parentheses.
[3] Number of insecticides applied for control of lepidopterous pests in parentheses.
[4] Includes peach twig borer, omnivorous leaf roller and codling moth.

Table 3. 1987 Mating disruption trials for the control of oriental fruit moth in California orchards[1]: Fruit damage from oriental fruit moth (OFM) and from other species. (adapted from Rice and Kirsch, in press)

		% Damage in treatments:		
Orchard	Pest	Pheromone	Comparison[2]	
Parlier	OFM	0.0	14.9	(0)
Fld. 21	Other[3]	0.7	16.2	
Parlier	OFM	0.1	14.9	(0)
Fld. 24	Other	0.0	16.2	
Parlier	OFM	0.3	1.6	(1)
Fld. 72	Other	0.3	11.6	
Kingsburg i.	OFM	0.0 *[4]	0.2	(0)
	Other	0.0	0.0	
Kingsburg ii.	OFM	0.0 *	0.1	
	Other	0.1	0.0	
Kingsburg iii.	OFM	0.1 *	0.2	
	Other	0.1	0.5	
Lomo-1	OFM	0.1	—	
	Other	0.1	—	
Lomo-2	OFM	0.2 *	—	
	Other	0.1		
Yuba City i.	OFM	0.0 *	—	
	Other	0.0	—	
Yuba City ii.	OFM	0.0	—	
	Other	0.0	—	
Live Oak	OFM	0.1	—	
	Other	0.6	—	

[1] Different cultivars of peach and nectarine.
[2] Number of insecticides applied for control of lepidopterous pests in parentheses.
[3] Includes peach twig borer, omnivorous leaf roller and codling moth.
[4]* Indicates this block was the comparison orchard in 1986, pheromone treated in 1987.

that mating disruption with synthetic pheromones is a feasible alternative in California to conventional insecticide sprays for this pest. Following these trials, the product was granted registration by the United States Environmental Protection Agency in December, 1986, and California state registration in February, 1987. In the initial year of commercial use, 1987, over 1500 acres of peaches were treated with pheromone, and this has more than doubled to nearly 3500 acres in 1988, the second year of commercial use.

Growers using the product typically see no need for insecticide applications (Stockwin, 1988). In some situations, however, one insecticide application is judged to be necessary for the control of immigrating mated female moths and/or secondary lepidopterous pests normally controlled by the broad spectrum insecticide applications. The potential for increased damage from these secondary lepidopterous pests (peach twig borer and omnivorous leafroller) in the absence of in-season sprays of insecticide for oriental fruit moth had been observed in the initial trial evaluations (Table 2).

Benefits of the mating disruption technique

Low toxicity

Mating disruption promises to be an alternative pest control technique useful for some key agricultural pests. The single most important benefit of using pheromones is their low toxicity (Beroza et al., 1975; Knipling, 1976; Kydonieus and Beroza, 1982). Toxicological tests performed on those compounds that have been subject to review by environmental protection agencies indicate that these materials have negligible mammalian toxicity (Table 4). Further, due to the low amounts used and the method of application, pheromones are not expected to have adverse effects on nontarget species (Ghassemi et al., 1983).

Ease of application

Ease of application is dependent on the formulation. Some formulations have required the development of expensive application equipment (Kydonieus et al., 1982), and this has limited their practicality in commercial use. However, polyethylene pheromone dispensers (currently used for oriental fruit moth, grape berry moth in North America, lesser peach tree borer, and peach tree borer) are easy to apply, requiring no special equipment. Applicators do not need to have the special training and protective clothing that are required in the use of conventional pesticides.

No regulatory restrictions

There are fewer regulatory restrictions involved in the use of pheromones compared to insecticides. Notices of intent prior to the use of pheromones do not need to be filed with local regulatory officials, and treated fields do not need to be posted against entry by unauthorized persons. Re-entry or preharvest intervals do not need to be observed. Due to the very low toxicity of naturally occurring pheromones, the instability of the active ingredient, and the very low levels of material applied in the field, there are no restrictions on the amount of pheromone residue on fruit at harvest.

Compatible with cultural practices

The use of pheromones for pest control is readily compatible with other cultural and production operations in agriculture. Pheromone applications are predictable on a calendar schedule, and other operations including irrigation, hand and mechanical cultivation, thinning, tree propping, pruning, and harvest can be easily scheduled without fear of interference from in-season insecticide applications. Cultural operations requiring large amounts of hand labor, e.g. thinning and hand cultivation, can be conducted at the proper time without any concern for insecticide residues.

Compatible with natural control agents

Relative to conventional broadly toxic insecticides, the use of pheromones allows preservation of beneficial biological control agents, as well as insect pollinators. Numbers of beneficial arthropods increase dramatically when toxic pesticides are no longer applied (e.g. Madsen and Madsen, 1982; Westigard and Moffit, 1984) and population levels of predatory insects are generally higher in pheromone-treated areas when compared to those in areas treated with insecticides (Critchley et al., 1985). It is anticipated that, with the continued use of pheromones to control key pests, increasing levels of biological control of secondary pests will be observed over time.

Pear psylla is a major pest of pears in the Pacific Northwest of the United States. Often, the organophosphate insecticides used to control codling moth in pears disrupt pear psylla population by interfering with levels of biological

Table 4. Comparison of the toxicology of some lepidopterous pheromones with that of a commonly used insecticide, azinphos-methyl.

Toxicology Test	Animal	Z8-12Ac E8-12Ac[3]	E3Z13-18Ac Z3Z13-18Ac[4]	Z7Z11-16Ac Z7E11-16Ac[5]	E4-13Ac[1]	Z6-21-11Kt[2]	E11-14A1 Z11-14A1[6]	Azinphos-methyl[7]
Toxicity—Single dose[8]								
Oral LD_{50}	Rat	NOEL[9] = >17.1g/kg	No adverse effects	NOEL = >15g/kg	No mortalities, 24 hr	NOEL = >5g/kg	NOEL = >5g/kg	M: 16mg/kg F: 13.5mg/kg
Dermal LD_{50}	Rat	NOEL = >20g/kg	No adverse effects	—	No mortalities, 13 days	—	NOEL = >5g/kg	M:455mg/kg F:220mg/kg
Primary skin irritation[10]	Rabbit	PI score: 0.96	No adverse effects	—	PI score: 0.93	PI score: <0.5	PI score: 1.7	—
Primary eye irritation	Rabbit	No effects observed	No adverse effects	—	No effects observed	Not an eye irritant	No +ve effect observed	—
Acute inhalation LC_{50}	Rat	NOEL = 74.7mg/l	No adverse effects	NOEL = >3.3mg/l	No morbidities or mortalities	No morbidities or mortalities	NOEL = 16.88 mg/l	M: 69 mg/kg F: 79 mg/kg
Mutagenicity studies								
Ames assay		Not mutagenic	—	Not mutagenic	Not mutagenic	—	—	Considered inactive
Short term dietary studies								
90-day	Rats	—	—	NOEL = >3,000 ppm	—	—	—	Depressed cholinesterase activity
90-day	Dogs	—	—	NOEL = >3,000 ppm	—	—	—	Cholinesterase activity decreased

[1] E4-13Ac = E4-tridecen-1-yl acetate. This compound is the only known component of tomato pinworm pheromone. Toxicology tests are reviewed in the Federal Register 46.197, pp. 50371-50372.

[2] Z6-21-11Kt = Z6-Heneicosen-11-one. This compound is the major component of douglas-fir tussock moth, *Orgyia pseudotsugata*, pheromone. Toxicology test results were provided by Dr. G. Daterman, USDA-Forestry Sciences Laboratory, Corvallis, Oregon.

[3] E8-12Ac = E8-dodecenyl acetate. These two isomers of dodecenyl acetate are major components of the oriental fruit moth pheromone. Toxicology tests are reviewed in the Federal Register 51.238, pp. 44605-44606.

[4] Z3Z13-18Ac = (Z,Z)-3,13-octadecadien-1-ol acetate. These two isomers of octadecadienol acetate are components of peachtree borer and lesser peachtree borer pheromone. Toxicology tests are reviewed in the Federal Register 46.94 pp. 26770-26771.

[5] Z7E11-16Ac = (Z,E)-7,11-hexadecadien-1-ol acetate. These two isomers of hexadecadienol acetate are components of the pink bollworm pheromone. Toxicology tests are reviewed in the Federal Register 43.94 pp. 20802-20803.

[6] Z11-14A1 = Z11-tetradecenal. These two isomers are components of the spruce budworm pheromone. Toxicology test results were provided by Dr. G. Daterman, USDA-Forestry Sciences Laboratory, Corvallis, Oregon.

[7] Azinphos-methyl is an organophosphate insecticide commonly used in agricultural pest control throughout the world. Toxicology is reviewed in the World Health Organisation Data Sheet on Pesticides #59. WHO/VBC/PDS/DS/85.59.

[8] Results given in mg/kg or g/kg indicate administered dosage of active ingredient in mg or g per kg body weight of the test animal.

[9] NOEL = No-observed-effect-level.

[10] PI score = 0.96, 0.93: active ingredient is a slightly irritating agent. PI score <0.5. active ingredient is not a skin irritant. (Federal Hazardous Substances Labeling Act Regulations, V. 38.187, Part 2.)

control agents (Westigard, 1973; Gut et al., 1981). With the elimination of these insecticides from pear orchards during a two-year study evaluating mating disruption of codling moth, natural control of pear psylla was enhanced through increased populations of their predators. Organophosphate insecticides reduced predator populations by ca. 90 percent when compared to levels remaining in pheromone-treated and untreated sections of the orchard (Westigard and Moffit, 1984). Direct psylla damage to the fruit averaged 1.5, 0.3, and 9.7 percent respectively in the pheromone-treated, untreated, and insecticide-treated plots. This reduction in fruit downgrading or loss of commercial utilization of the fruit represented a considerable economic savings to the grower.

Biological control of phytophagous mites in crops treated with pheromones for mating disruption of key pests will also be enhanced through the elimination of most broad spectrum insecticides. This has been experienced in peaches in Australia (John Slack, personal communication) and California (Weakley et al., 1987; Rice and Kirsch, in press). This benefit of pheromones will become increasingly more important as the availability of miticides is further limited by regulatory action (e.g. cyhexatin in California in 1987). As well, increasing levels of mite resistance to a broad range of these materials are dictating the adoption of programs maximizing the activity of natural biological control agents. Pheromones do not interfere with such programs.

Resistance is unlikely

It is unlikely that insects will develop resistance as readily to pheromone-based control strategies as they have to all major classes of insecticides. Mating disruption of pink bollworm has been undertaken for over eight years, yet

Haynes and Baker (1988) were unable to show any effective resistance in populations subject to continuous disruption pressure. Haynes et al. (1984) and Haynes and Baker (1988) argue that selection for resistance may be difficult because it would involve changes in both males and females, unless there is close genetic linkage between emission and response.

Long-term population reduction

Finally, pheromones may ultimately offer an opportunity to reduce target pest populations over the longer term. This effect has been observed in Australia, where growers have used mating disruption over three or more successive seasons for the control of oriental fruit moth (John Slack, personal communication). A similar trend has also been noted in oriental fruit moth trials in northern California (unpublished data).

Limitations of mating disruption

Immigration of mated females

Mating disruption does not prevent damage that may result from immigration (or extended host searching) of mated female insects from sources external to the field treated with pheromone (Rothschild 1975, 1981, 1982; Moffit and Westigard, 1984). As a result, it is essential to try and treat complete crop units. Single tree evaluations and small plot trials placed within large non-pheromone treated blocks need to be avoided. As a result, the technique probably has little promise for household garden or backyard use (Reissig, et al., 1984).

Secondary pests

Mating disruption is a very species-specific control tactic. This has disadvantages as well as advantages. Nontarget pest species controlled by broad-spectrum pesticides in current management programs may reach damaging population levels in the absence of these sprays. This has been observed in the implementation of oriental fruit moth mating disruption in California (Table 2) and in preliminary evaluation of codling moth mating disruption in California pears (Table 5). It may be that the greatest likelihood for successful adoption of mating disruption in pest management will be in situations where there is only one important pest species and secondary pest problems arise through pesticide treatments directed at the key pest.

In apple *(Pyrus malus)* pest management in North America, pest and beneficial arthropod populations fluctuate widely between different areas and under varied pesticide programs (Madsen and Madsen, 1982). In the northeast, studies evaluating fruit damage to apples following total omission of insecticides and acaricides demonstrate very high levels of damage from a broad complex of species including nontarget pests (Glass and Lienk, 1971; Hagley et al., 1977), although effective control of this complex can often be achieved through a well-timed minimal spray program (Hagley et al., 1977; Hull et al., 1983; Reissig et al., 1984). On the other hand, the pest complex in the Pacific Northwest is less diverse and may be more suited for mating disruption.

In evaluation of a species-specific codling moth control tactic in apples in British Columbia, Madsen and Carty (1979) achieved excellent control of nontarget lepidoptera using two supplementary applications of *Bacillus thuringiensis*. Preliminary evaluation of codling moth mating disruption in California pears (Table 5) suggests that satisfactory levels of lepidopterous pest control may be achieved when pheromone is supplemented with one or two well-timed insecticides. This supplementary insecticide program will probably consist of one application of *Bacillus thuringiensis* and one application of an organophosphate (Weakley and Kirsch, unpublished data).

Pest management programs utilizing mating disruption will need to be independently evaluated for best fit in these variable pest complexes and populations. For example, where a large complex of species attacks peaches in southeastern North America, it may not be possible to find a fit for mating disruption for one species, whereas the approach fits very well and has been adopted commercially in management of the less diverse peach pest complex of the western United States (Weakley et al., 1987; Rice and Kirsch, in press). In California, a properly applied dormant application of a broadly toxic insecticide often provides sufficient population suppression of peach twig borer *(Anarsia*

Table 5. Per cent Lepidopterous damage, to pears at harvest, in a 1987 trial integrating codling moth pheromone for control of the major pest with insecticides for control of secondary pests.[1] (Kirsch, Weakley and Studdert, unpublished results)

Treatment[2]	Codling Moth[3]	Leafroller Complex[4] Early season[5]	Leafroller Complex[4] Mid-late season[6]	Total
Pheromone only	0.36	1.77 ab	13.41 a	15.54
Pher + 1 spray (1 early)	0.0	0.34 b	2.28 c	2.62
Pher + 3 sprays (1 early, 2 mid)	0.0	0.31 b	0.36 c	0.67
Pher + 3 sprays (2 mid, 1 late)	0.01	1.76 ab	1.65 c	3.42
Pher + 1 spray (1 late)	0.16	2.37 b	7.39 b	9.92
Insecticide Control (5 sprays)	0.04	0.23	0.15	0.41

[1] Damage results are based on a sample of 7500 fruit/treatment.
[2] The timing of supplementary insecticide applications is in parentheses.
[3] Treatments not significantly different at the 0.05 level.
[4] Leafroller complex includes fruittree leafroller (*Archips argyrospila*) obliquebanded leafroller (*Choristoneura rosaceana*) and omnivorous leafroller.
[5] Treatments followed by the same letter are not significantly different at the 0.05 level.

lineatella), a secondary nontarget pest, and eliminates the need for in-season insecticides following commercial implementation of oriental fruit moth mating disruption (Rice and Kirsch, in press).

Kydonieus and Beroza (1982) suggest that pheromones will be too costly to use on crops having more than a few arthropod pests that require control. However, in such situations, control of key pests with pheromones could be a valuable component of pest management programs integrating pheromones with insecticides (Critchley et al., 1983), and it is to be expected that continued experimentation with and use of pheromones for control of key pests will result in a satisfactory balance being found between pheromones and conventional insecticides for control of the whole pest complex (Critchley et al., 1985).

Breakdown of control under high pest populations

Mating disruption will quite likely be ineffective as a control technique when used against very high populations of the target pest. The relationship between efficacy of mating disruption and pest density would be the same as for application of insecticides and other methods of control. If disruption of mate finding is largely due to interference with the long-range guidance mechanism that insects use, "then the density of the pest will influence the effectiveness of the confusion treatment regardless of secondary and shorter range stimuli, such as vision, that may be involved" (Knipling, 1979, p. 465).

The 1986 Parlier Field 21 trial (Table 2) is an example of a situation where pheromone in the first year of application was apparently unable to entirely overcome the impact of a high residual oriental fruit moth population, resulting in 14.2 percent damage to the fruit at harvest. (Oriental fruit moth fruit infestation levels exceeded 35 percent at harvest in 1985, even following the application of two insecticide sprays.) When retreated with pheromone in 1987, damage from oriental fruit moth was not detected at harvest (Table 3). In trials evaluating codling moth mating disruption, application of the pheromone was ineffective in substantially reducing fruit infestation levels over two years when targeted against a very high endemic pest population (Moffit and Westigard, 1984). In the same trial, mating disruption did suppress codling moth populations at lower pest densities.

Where there are high endemic populations of the target insect, it may be necessary to reduce the population pressure with an insecticide application in the initial year of pheromone use. In the 1986 Yuba City oriental fruit moth disruption trial (Table 2), an insecticide application was directed at the second generation of the pest to help reduce the population to a level at which the pheromone could achieve satisfactory mating disruption. In 1987, following retreatment with a single application of pheromone, damage from oriental fruit moth could not be detected in fruit at harvest (Table 3).

Cost

Possibly the major factor limiting the widespread development and implementation of pheromones is still the cost of synthesis of active ingredient. As a result, commercialization of the technique is currently limited to control of key pests of high-value crops that are presently protected by expensive conventional spray programs or control of pests of large acreage crops such as cotton. Mating disruption will become more competitive with the development of dispensing systems that release pheromone more efficiently.

Ultimately, the current regulatory climate and consumer pressure for pesticide-free produce (Aylsworth, 1988; Mueller, 1988; Wearing, 1988) may force the adoption of biologically based pest management techniques regardless of the costs involved.

Pest characteristics favoring mating disruption control with pheromones

The decision of whether any pheromone, despite its availability, should be used in direct control is dictated by a set of factors intrinsic and extrinsic to the pest. Extrinsic factors, such as availability of reliable dispenser technology, dispenser use pattern, cost of active ingredient, potential market value, and potential market size, directly influence the decision industry makes when choosing whether or not to proceed with research and development of a new mating disruption product. Decisions to develop new products are profit-driven and integrated pest management or environmental safety are often not important influences in the decision-making process (Mueller, 1988). For example, although commercially acceptable levels of artichoke plume moth control using pheromones were demonstrated in 1981 (Haworth et al., 1982), six years later Birch (1987) indicated that any widespread commercial use of mating disruption in this crop is still restricted to discussions in the realms of "business, politics, and prayers."

Intrinsic factors concerning the biology and ecology of the pest will directly influence the potential for success of attempts at mating disruption. For example, cotton bollworm *(Heliothis* spp.*)* is a major agricultural pest of crops worldwide, yet the high mobility of this insect makes it a less suitable candidate for disruption purposes, and mating disruption for the control of *Heliothis* spp. has met with little success. The pheromone biology of spruce budworm, *(Choristoneura fumiferana)*, a major pest of Canadian forestry, has been studied extensively. Nevertheless, a number of attempts at mating disruption have not proved very successful due in part to invasion of gravid females (Sanders, 1981a). A number of authors have discussed characteristics of pests that determine their suitability for control with pheromones (Campion, 1984; Kiritani and Kanoh, 1984; Rothschild, 1981; Sternlicht, 1986).

Summary

Many insects rely on behavior-modifying chemicals for the purpose of communication. Pheromones are released for intraspecific communication and sex pheromones are used as a means of communication between male and female insects of one species. Presently, the major

use of pheromones in pest management is in monitoring and detection, and this has lead to decreases in the use of pesticides in some situations. Monitoring of pests with pheromones has resulted in more efficient pesticide usage by timing pesticide applications correctly. Development of the use of pheromones in direct pest control strategies has been limited by a number of factors including incomplete identification of pheromone chemicals, inadequate pheromone dispensing technology, the high cost of synthetic active ingredient, and often a poor understanding of the biology of the pest.

With the development of new controlled release systems, mating disruption using sex pheromones has been demonstrated to be an alternate strategy for the control of oriental fruit moth, grape berry moth in North America and Europe, pink bollworm, lesser peach tree borer, peach tree borer, and tomato pinworm. Introduction of mating disruption has met with commercial success for some of these pests, notably oriental fruit moth and pink bollworm. Mass-trapping has been shown to be very effective in the control of some beetle pests in forestry and agriculture.

Expansion in the future development of strategies using pheromones for the control of insects is dependent on a number of factors. An in-depth understanding of the biology and ecology of the pest is essential to the development of strategies that control by interference with pest behavior. Future studies will also need to address the behavior of synthetic pheromone formulations in the field and try to relate this to the behavior of the pest. A greater understanding in both of these areas will lead to the design of controlled release devices that better manipulate behavior of the pest within given physical and climatic parameters of the target pests' environment.

The use of pheromones in manipulation of insect communication for control of pests has been proposed for over 25 years. In the last 5 years, a resurgence of interest in developing mating disruption strategies for pest control has lead to the commercialization of new formulations for the control of oriental fruit moth and pink bollworm worldwide, the control of the tea tortrix complex in Japan, and control of the European grape berry moth in the Federal Republic of Germany. Products for the control of grape berry moth in the American northeast, tomato pinworm in California and Mexico, and lesser peach tree borer and peach tree borer in North America are very near commercialization.

Government support of the development of mating disruption strategies will help speed their introduction by industry. Grants could initially target three areas: a) the development of commercially competitive synthetic pathways for pheromone active ingredient; b) the development of controlled release systems; and c) the performance of large-scale field trials to demonstrate efficacy against economically important pest species. The introduction of minimal data requirements for product efficacy testing (experimental use permits) would accelerate research and development of potential pheromone-based control strategies for other arthropod pests.

Commercialization of pheromones for insect control will continue to expand. In the past, successful introduction of this technique has come through careful field research, most often in cooperation between high technology industries, multi-disciplinary public sector research organizations, and primary producer groups. Cautious technically based commercial development of this preliminary field research and technically sound marketing has resulted in growing consumer acceptance of this approach for control of arthropod pests that have been targeted. Ongoing success in the area of mating disruption will lead to the exploitation of other behavior-modifying chemicals in pest control. The rapid development of such alternatives as these is one of the most important challenges faced in making safe and efficient use of managed ecosystems.

References

1. Anonymous. 1986. Pheromones. Product Bulletin. Shin Etsu Chemical Co., Ltd., Tokyo, Japan. pp. 3-4.
2. Antle, J. M., and S. K. Park. 1986. The economics of IPM in processing tomatoes. California Agriculture 40(3-4):31-32.
3. Arn, H., P. M. Guerin, H. R. Buser, S. Rauscher, and E. Mani. 1985. Sex pheromone blend of the codling moth, *Cydia pomonella*. Evidence for a behavioural role of dodecan-1-ol. Experientia 41:1482-1484.
4. Arn, H., M. Toth, and E. Priesner. 1986. List of sex pheromones of lepidoptera and related attractants. Organisation Internationale de Lutte Biologique, Paris, France. 120 pp.
5. Aylsworth, J. 1988. Who's calling the shots? Western Fruit Grower 108(4):16-17.
6. Baker, T. C. 1985. Chemical control of behaviour. In G. A. Kerkut and L. I. Gilbert (eds.). Comprehensive Insect Physiology, Biochemistry and Pharmacology. Vol. 9: Behaviour. Pergamon Press, Oxford. pp. 621-672.
7. Baker, T. C., and R. T. Cardé. 1979. Analysis of pheromone mediated behaviour in male *Grapholitha molesta*, the oriental fruit moth (Lepidoptera: Tortricidae). Environ. Entomol. 8:956-968.
8. Baker, T. C., R. T. Staten, and H. M. Flint. Use of pink bollworm pheromone in the southwestern United States. In R. Ridgway, R. M. Silverstein, and M. Inscoe (eds.). Practical Applications of Insect Pheromones and Other Attractants. Marcel Dekker, New York, New York. In Press.
9. Barrer, P. M. 1976. The influence of delayed mating on the reproduction of *Ephestia cautella* (Walker) (Lepidoptera: Phycitinae). J. Stored Product Res. 12:165-169.
10. Bartell, R. J. 1977. Behavioural responses of lepidoptera to pheromones. In H. H. Shorey (ed.). Chemical Control of Insect Behaviour. Theory and Application. Wiley and Sons, New York, New York. pp. 201-213.
11. Bartell, R. J. 1982. Mechanisms of communication disruption by pheromone in the control of Lepidoptera: a review. Physiol. Entomol. 7:353-364.
12. Bartell, R. J., and T. E. Bellas. 1981. Evidence for naturally occurring secondary compounds of the codling moth sex pheromone. J. Australian Entomol. Soc. 20:197-199.
13. Beroza, M. 1960. Insect attractants are taking hold. Agricultural Chemistry 15:37-40.
14. Beroza, M., M. N. Inscoe, P. H. Schwartz, Jr., M. L. Keplinger, and C. W. Mastri. 1975. Acute toxicity studies with insect attractants. Toxicol. Appl. Pharmacol. 31:421-429.
15. Bestman, H. J., and O. Vostrowsky. 1988. Pheromones of the coleoptera. In E. D. Morgan and N. B. Mandava (eds.). CRC Handbook of Natural Pesticides. Vol. IV: Pheromones, Part A. CRC Press, Boca Raton, Florida. pp. 95-183.
16. Birch, M. C. 1987. An overview of mating disruption in the artichoke plume moth. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp. 25-26.
17. Booth, W. 1988. Revenge of the "nozzleheads." Science 239:135-137.
18. Burkholder, W. E., and M. Ma. 1985. Pheromones for monitoring and control of stored product insects. Annual Rev. Entomol. 30:257-272.
19. Butenandt, A., R. Beckman, D. Stamm, and E. Hecker. 1959. Uber den Sexuallockstoff des Seidenspinner *Bombyx mori*, Reidarstellung und Konstitution. Zeitschrift Naturforschung B 14:283-284.

20. Campion, D. G. 1984. Summary of pheromone uses in pest control. In H. E. Hummel and T. A. Miller (eds.). Techniques in Pheromone Research. Springer-Verlag, New York, New York. pp. 405-449.
21. Campion, D. G., and F. Nesbitt. 1982. Recent advances in the use of pheromones in developing countries with particular reference to mass-trapping for the control of the Egyptian cotton leafworm *Spodoptera littoralis* and mating disruption for control of the pink bollworm *Pectinophora gossypiella*. In Les mediateurs chimiques agissant sur le comportement des insectes. Symp. Int. Versailles 16-20 Nov. 1981. INRA Publ. #7 1982. pp. 335-342.
22. Cardé, R. T. 1981. Disruption of long distance pheromone communication in the oriental fruit moth: camouflaging the natural aerial trails from females. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 385-397.
23. Cardé, R. T., T. C. Baker, and P. J. Castrovillo. 1977. Disruption of sexual communication in *Laspeyresia pomonella* (codling moth), *Grapholitha molesta* (oriental fruit moth) and *G. prunivora* (lesser appleworm) with hollow fibre attractant sources. Entomologia Experimentalis et Applicata 22:280-288.
24. Charlton, R. E., and R. T. Cardé. 1981. Comparing the effectiveness of sexual communication disruption in the oriental fruit moth (Grapholitha molesta) using different combinations and dosages of its pheromone blend. J. Chem. Ecol. 7:501-508.
25. Charmillot, P. J. 1987. Some considerations on mating disruption of codling moth *Cydia pomonella* and summerfruit tortrix *Adoxophyes orana* in apple orchards. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp. 11-16.
26. Cook, R. J., L. Andres, G. A. de Zoeten, C. Doane, R. W. Gwadz, R. Hardy, B. Hemming, J. Kuc, R. Mankau, D. Miller, C. A. Ryan, and S. Smith. 1987. Report of the research briefing panel on biological control in managed ecosystems. In Research Briefings 1987. National Academy Press, Washington, DC. pp. 1-12.
27. Critchley, B. R., D. G. Campion, L. J. McVeigh, P. Hunter-Jones, D. R. Hall, A. Cork, B. F. Nesbitt, G. J. Marrs, A. R. Jutsum, M. M. Hosny and El-Sayed A. Nasr. 1983. Control of pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), in Egypt by mating disruption using an aerially applied microencapsulated pheromone formulation. Bull. Entomol. Res. 73:289-299.
28. Critchley, B. R., D. G. Campion. L. J. McVeigh, E. M. McVeigh, G. G. Cavanagh, M. M. Hosny, El-Sayed A. Nasr, A. A. Khidr, and M. Naguib. 1985. Control of pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), in Egypt by mating disruption using hollow fibre, laminate-flake and microencapsulated formulations of pheromone. Bull. Entomol. Res. 75:329-345.
29 Davidson, S. 1985. Confusion control of the oriental fruit moth. Rural Research 126:9-12. (CSIRO Australia).
30. Dennehy, T. J., W. L. Roelofs, E. F. Taschenberg, and T. N. Taft. Mating disruption for control of grape berry moth in New York vineyards. In R. Ridgway, R. M. Silverstein, and M. Inscoe (eds.). Practical Applications of Insect Pheromones and Other Attractants. Marcel Dekker, New York, New York. In Press.
31. Doane, C. J., and T. W. Brooks. 1981. Research and development of pheromones for insect control with emphasis on the pink bollworm. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 285-303.
32. Dunkelblum, E., M. Kehat, and S. Gothilf. 1987. Mating disruption of the cotton leafworm, *Spodoptera littoralis*, monitored by direct night observation. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp. 27-29.
33. Einhorn, J., F. Beauvais, M. Gallois, C. Descoins, and R. Causse. 1984. Constituants secondaires de la pheromone sexuelle du Carpocapse des Pommes, *Cydia pomonella* L. (Lepidoptera: Tortricidae). C. R. Acad. Sc. Paris, t. 299, Serie III 19:273-278.
34. Einhorn, J., P. Witzgall, H. Audemard, B. Boniface, and R. Causse. 1986. Secondary components of the codling moth (Cydia pomonella L.). C. R. Acad. Sci. 302:262-266.
35. Englert, W. D. 1987. Mating disruption in field populations of the grape berry moth *Eupoecilia ambiguella* (Hb.) (Lep. Tortricidae, Cochilini) with Z-9-dodecenyl acetate. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp. 7-8.
36. Field, R. P. 1976. Integrated pest control in Victorian peach orchards: The role of *Typhlodromus occidentalis* Nesbitt (Acarina: Phytoseiidae). Australian J. Zool. 24:265-272.
37. Fletcher, B. S., and T. E. Bellas. 1988a. Pheromones of Diptera. In E. D. Morgan and N. B. Mandava (eds.). CRC Handbook of Natural Pesticides, Vol. IV: Pheromones, Part B. CRC Press, Boca Raton, Florida. pp. 1-57.
38. Fletcher, B. S., and T. E. Bellas, 1988b. Pheromones of Hemiptera, Blattodea, Orthoptera, Mecoptera, other insects and Acari. In E. D. Morgan and N. B. Mandava (eds.). CRC Handbook of Natural Pesticides, Vol. IV: Pheromones, Part B. CRC Press, Boca Raton, Florida. pp. 207-271.
39. Frisbie, R. E., and P. L. Adkisson (eds.). 1985. CIPM: Integrated pest management on major agricultural systems. Texas Agricultural Experiment Station MP-1616. 743 pp.
40. Gentry, C. R., B. A. Bierl-Leonhardt, J. L. Blythe, and J. R. Plimmer. 1980. Air permeation tests with orfralure for reduction in trap catch of oriental fruit moths. J. Chem. Ecol. 6:185-192.
41. Gentry, C. R., M. Beroza, J. L. Blythe, and B. A. Bierl. 1975. Captures of the oriental fruit moth, the pecan bud moth, and the lesser appleworm in Georgia field trials with isomeric blends of 8-dodecenyl acetate and air permeation trials with the oriental fruit moth pheromone. Environ. Entomol. 4:822-824.
42. Georghiou, G. P. 1986. The magnitude of the resistance problem. In NRC, Board on Agriculture, Pesticide resistance: strategies and tactics for management. National Academy Press, Washington, DC.
43. Ghassemi, M., P. Painter, S. Quinllvan, and M. Dellarco. 1983. *Bacillus thuringiensis*, nucleopolyhedrosis virus and pheromones: Environmental considerations and uncertainties in large-scale insect control. Environment International 9:39-49.
44. Glass, E. H., and S. E. Lienk. 1971. Apple insect and mite populations developing after discontinuance of insecticides: 10 year record. J. Econ. Entomol. 64:23-26.
45. Gut, L., P. Westigard, W. Liss, and M. Willet. 1981. Biological control of pear psylla: a potential within a potential. Proc. Wash. Hortic. Assn. 77:194-198.
46. Hagley, E. A. C., L. G. Monteith, D. H. C. Herne, and R. Trottier. 1977. Pest population buildup in apple orchards following omission of insecticide and acaricide sprays. Proc. Entomol. Soc. Ontario 108:7-11.
47. Hassan, S. A., R. Albert, F. Bigler, P. Blaisinger, H. Bogenschutz, E. Boller, J. Brun, P. Chiverton, P. Edwards, W. D. Englert, P. Huang, C. Inglesfield, E. Naton, P. A. Oomen, W. P. J. Overmeer, W. Rieckmann, L. Samsoe-Petersen, A. Staubli, J. J. Tuset, G. Viggiani, and G. Vanwetswinkel. 1987. Results of the third joint pesticide testing programme by the IOBC/WPRS-Working Group "Pesticides and Beneficial Organisms." J. Appl. Entomol. 103:92-107.
48. Haworth, J. K., R. P. Puck, I. Weatherston, C. C. Doane, and S. Ajeska. 1982. Research and development of a mating disruptant for control of the artichoke plume moth, *Platyptilia carduidactyla* (Riley) (Lepidoptera: Pterophoridae). In Les mediateurs chimiques agissant sur le comportement des insectes. Symp. Int. Versailles 16-20 Nov. 1981. INRA Publ. #7 1982. pp. 343-356.
49. Haynes, K. F., and T. C. Baker. 1985. Sublethal effects of permethrin on the chemical communication system of the pink bollworm moth, *Pectinophora gossypiella*. Arch. Insect Biochem. and Physiol. 2:283-293.
50. Haynes, K. F., and T. C. Baker. 1988. Potential for evolution of resistance to pheromones. Worldwide and local variation in chemical communication system of pink bollworm moth, *Pectinophora gossypiella*. J. Chem. Ecol. 14:1547-1560.
51. Haynes, K. F., L. K. Gaston, M. M. Pope, and T. C. Baker. 1984. Potential for evolution of resistance to pheromones: Interindividual and interpopulational variation in chemical communication system of pink bollworm moth. J. Chem. Ecol. 10:1551-1565.
52. Haynes, K. F., T. A. Miller, R. T. Staten, W. Li, and T. C. Baker. 1986. Monitoring insecticide resistance with insect pheromones. Experientia 40:1293-1295.
53. Haynes, K. F., T. A. Miller, R. T. Staten, W. Li, and T. C. Baker. 1987. Pheromone trap for monitoring insecticide resistance in the pink bollworm moth (Lepidoptera: Gelechiidae): New tool for resistance management. Environ. Entomol. 16:84-89.
54. Headley, J. C., and M. A. Hoy. 1986. The economics of integrated mite management in almonds. California Agriculture 40(1-2):28-30.

55. Henneberry, T. J., L. A. Bariola, H. M. Flint, P. D. Lingren, J. M. Gillespie, and A. F. Kydonieus. 1981. Pink bollworm and tobacco budworm mating disruption studies on cotton. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 267-284.
56. Hill, D. S. 1975. Agricultural Insect Pests of the Tropics and Their Control. Cambridge University Press, Cambridge, U.K. p. 275.
57. Hoyt, S. C., P. H. Westigard, and E. C. Burts. 1978. Effects of two synthetic pyrethroids on the codling moth, pear psylla, and various mite species in northwest apple and pear orchards. J. Econ. Entomol. 71:431-434.
58. Hull, L. A., K. D. Hickey, and W. W. Kanour. 1983. Pesticide usage patterns and associated pest damage in commercial apple orchards of Pennsylvania. J. Econ. Entomol. 76:577-583.
59. Jimenez, M. J., N. C. Toscano, D. L. Flaherty, P. Ilic, F. G. Zalom, and K. Kido. 1988. Controlling tomato pinworm by mating disruption. California Agriculture 42(6):10-12.
60. Jutsum, A. R., G. J. Marrs, R. F. S. Gordon, D. G. Campion, B. R. Critchley, L. J. McVeigh, A. Cork, D. R. Hall, B. F. Nesbitt, M. M. Hosny, and A. Nasr El-Sayed. 1983. Control of crop pests with microencapsulated pheromones. Proc. Int. Cong. Plant. Protection 10th. pp. 266-267.
61. Karlson, P., and M. Luscher. 1959. Pheromones: a new term for a class of biologically active substances. Nature 183:55-56.
62. Kennedy, J. W. 1981. Practical application of pheromones in regulatory pest management programs. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 1-11.
63. Kiritani, K., and M. Kanoh. 1984. Influence of delay in mating on the reproduction of the oriental tea tortrix, *Homona magnanima* Diakonoff (Lepidoptera: Tortricidae), with reference to pheromone-based control. Protection Ecology 6:137-144.
64. Klun, J. A. 1985. Sexual messages of moths: Chemical themes are known and new research challenges arise. In P. A. Hedin (ed.). Bioregulators for Pest Control. Amer. Chem. Soc. Symp. Series. 276:381-391.
65. Klun, J. A., J. W. Neal, Jr., B. A. Leonhardt, and M. Schwarz. 1986. Suppression of female bagworm, *Thyridopteryx ephemeraeformis*, reproduction with its sex pheromone 1-methylbutyl decanoate. Entomologia Experimentalis et Applicata 40:231-238.
66. Knipling, E. F. 1976. Role of pheromones and kairomones for insect suppression systems and their possible health and environmental impacts. Environ. Health Perspectives 14:145-152.
67. Knipling, E. F. 1979. The basic principles of insect population suppression and management. U.S. Department of Agriculture, Agricultural Handbook No. 512. 623 pp.
68. Kydonieus, A. F., and M. Beroza. 1982. Marketing and economics in use of pheromones for suppression of insect populations. In A. F. Kydonieus, M. Beroza, and G. Zweig (eds.). Insect Suppression with Controlled Release Systems, Vol. II. CRC Press, Boca Raton, Florida. pp. 187-199.
69. Kydonieus, A. F., J. M. Gillespie, M. W. Barry, J. Welch, T. J. Henneberry, and B. A. Leonhardt. 1982. Formulations and equipment for large volume pheromone applications by aircraft. In B. A. Leonhardt and M. Beroza (eds.). Insect Pheromone Technology: Chemistry and Applications. Amer. Chem. Soc. Symp. Ser. 190. pp. 175-191.
70. Legget, J. E., W. A. Dickerson, and E. P. Lloyd. 1988. Suppressing low level boll weevil populations with traps: influence of trap placement, grandlure concentration and population level. Southwestern Entomologist 13:205-216.
71. Lie, R. 1984. Mass trapping of *Ips typographus* with pheromone baited traps. In W. Y. Garner and J. Harvey, Jr. (eds.). Chemical and Biological Control in Forestry. Amer. Chem. Soc. Symp. Series. 238:49-53.
72. Lingren, P. D. 1983. Behaviour of pink bollworm (Lepidoptera: Gelechiidae) adults during eclosion to departure from site of emergence. Annals Entomol. Soc. Amer. 76:657-660.
73. Madsen, H. F. 1981. Monitoring codling moth populations in British Columbia apple orchards. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 57-62.
74. Madsen, H. F., and B. E. Carty. 1977. Pest management: Four years experience in a commercial apple orchard. J. Entomological Soc. British Columbia 74:3-6.
75. Madsen, H. F., and B. E. Carty. 1979. Organic pest control: Two years experience in a commercial apple orchard. J. Entomological Soc. British Columbia 76:3-5.
76. Madsen, H. F., and B. J. Madsen. 1982. Populations of beneficial and pest arthropods in an organic and a pesticide treated apple orchard in British Columbia. Can. Entomol. 114:1083-1088.
77. Madsen, H. F., J. M. Vakenti, and F. E. Peters. 1976. Codling moth: Suppression by male removal with sex pheromone traps in an isolated apple orchard. J. Econ. Entomol. 69:597-599.
78. Mani, E., F. Schwaller, and W. Riggenbach. 1984. Control of the codling moth (*Cydia pomonella* L.) with the disruption method in an orchard in the upper Rhine Valley. Mitt. Schweiz. Entomol. Gesellschaft 57:341-348.
79. Mani, E., F. Schwaller, and W. Riggenbach. 1987. Trap catches as indicators of disruption efficiency and uniformity of pheromone dispersal in *Cydia pomonella* trials. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. p. 17.
80. McVeigh, L. J., B. R. Critchley, and D. G. Campion. 1983. Control of the pink bollworm in Egypt by mating disruption using pheromones. Proc. Int. Cong. Plant. Protection 10th. p. 268.
81. Metcalf, R. L., and W. Luckman. 1975. Introduction to Pest Management. John Wiley and Sons, New York, New York. p. 4.
82. Miller, E., E. Jones, and R. Staten. 1986. The use of moth scales to determine male pink bollworm visitation to individual pheromone dispensers in a mating disruption system. Southwestern Entomologist 11:42-44.
83. Moffitt, H. R., and P. H. Westigard. 1984. Suppression of the codling moth (Lepidoptera: Tortricidae) population on pears in southern Oregon through mating disruption with sex pheromone. J. Econ. Entomol. 77:1513-1519.
84. Mueller, W. 1988. IPM: a wise discipline. So why hasn't it caught on? Agrichemical Age 32(5):6-7, 10, 22-23.
85. Neumann, U. 1987. BASF trials programme on the mating disruption technique with sexual attractants: Results obtained with the grape berry moth (*Eupoecilia ambiguella*). In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp. 9-10.
86. Palaniswamy, P., and W. D. Seabrook. 1985. The alteration of calling behaviour by female *Choristoneura fumiferana* when exposed to synthetic sex pheromone. Entomologia Experimentalis et Applicata 37:13-16.
87. Postel, S. 1988. Controlling toxic chemicals. In L. R. Brown (ed.). State of the World 1988. W. W. Norton and Company, New York, New York. pp. 118-136.
88. Reissig, W. H., M. Novak, and W. L. Roelofs. 1978. Orientation disruption of *Argyrotaenia velutinana* and *Choristoneura rosaceana* male moths. Environ. Entomol. 7:631-632.
89. Reissig, W. H., R. W. Weires, G. C. Forshey, W. L. Roelofs, R. C. Lamb, and H. S. Aldwinckle. 1984. Insect management in disease resistant dwarf and semi-dwarf apple trees. Environ. Entomol. 13:1201-1207.
90. Rice, R. E., and P. A. Kirsch. Mating disruption of oriental fruit moth in the United States. In R. Ridgway, R. M. Silverstein, and M. Inscoe (eds.). Practical Applications of Insect Pheromones and Other Attractants. Marcel Dekker, New York, New York. In Press.
91. Rice, R. E., C. V. Weakley, and R. A. Jones. 1984. Using degree days to determine optimum spray timing for the oriental fruit moth (Lepidoptera: Tortricidae). J. Econ. Entomol. 77:698-700.
92. Riedl, H., A. Seaman, and F. Henrie. 1985. Monitoring susceptibility to azinphos-methyl in field populations of the codling moth (Lepidoptera: Tortricidae) with pheromone traps. J. Econ. Entomol. 78:692-699.
93. Riedl, H., J. F. Howell, P. S. McNally, and P. H. Westigard. Codling moth management. Use and standardization of pheromone trapping systems. University of California, Division of Agriculture and Natural Resources. Bulletin 1918.
94. Roelofs, W. L., A. Comeau, and R. Seele. 1969. Sex pheromone of the oriental fruit moth. Nature 224:723.
95. Roelofs, W. L., A. Comeau, A. Hill, and G. Milicevic. 1971. Sex attractant of the codling moth: Characterization with electroantennogram technique. Science 174:297-299.
96. Roelofs, W. L., R. T. Cardé, E. F. Taschenberg, and R. M. Weires, Jr. 1976. Pheromone research for the control of lepidopterous pests in New York. In M. Beroza (ed.). Pest Management with Insect Sex Attractants. Amer. Chem. Soc. Symp. Ser. 23:75-87.
97. Rothschild, G. H. L. 1975. Control of the oriental fruit moth (*Cydia molesta* (Busck) (Lepidoptera: Tortricidae)) with synthetic sex pheromone. Bull. Entomol. Res. 65:473-490.
98. Rothschild, G. H. L. 1979. A comparison of methods of dispensing synthetic sex pheromone for the control of oriental fruit moth,

Cydia molesta (Busck) (Lepidoptera: Tortricidae), in Australia. Bull. Entomol. Res. 69:115-127.
99. Rothschild, G. H. L. 1981. Mating disruption of lepidopterous pests: Current status and future prospects. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 207-228.
100. Rothschild, G. H. L. 1982. Suppression of mating in codling moths with synthetic sex pheromone and other compounds. In A. F. Kydonieus, M. Beroza, and G. Zweig (eds.). Insect Suppression with Controlled Release Systems, Vol. II. CRC Press, Boca Raton, Florida. pp. 117-134.
101. Sanders, C. J. 1981a. Disruption of spruce budworm mating: State of the art. In E. R. Mitchell (ed.). Management of Insect Pests with Semiochemicals. Plenum Press, New York, New York. pp. 339-349.
102. Sanders, C. J. 1981b. Spruce budworm.: Effects of different blends of sex pheromone components on disruption of male attraction. Experientia 37:1176-1178.
103. Sanders, C. J. 1982a. Disruption of male spruce budworm orientation to calling females in a wind tunnel by synthetic pheromone. J. Chem. Ecol. 8:493-506.
104. Sanders, C. J. 1982b. Behaviour of spruce budworm male moths in pheromone permeated air in a wind tunnel. In Les mediateurs chimiques agissant sur le comportement des insectes. Symp. Int. Versailles 16-20 Nov. 1981. INRA Publ. #7 1982. pp. 203-216.
105. Sanders, C. J. 1986. The role of pheromone concentration in male moth flight behaviour. In T. L. Payne, M. C. Birch, and C. E. J. Kennedy (eds.). Mechanisms in Insect Olfaction. Clarendon Press, Oxford. pp. 117-122.
106. Sanders, C. J. 1987. Research on mating behaviour and its importance for developing techniques of mating disruption. In H. Arn (ed.). Mating Disruption: Behaviour of Moths and Molecules. Bulletin of the International Organisation for Biological Control - West Palaearctic Regional Section. pp.30-31.
107. Shapas, T. J., W. E. Burkholder, and G. M. Boush. 1977. Population suppression of *Trogoderma glabrum* by using pheromone luring for protozoan pathogen dissemination. J. Econ. Entomol. 70:469-474.
108. Shaw, R. H. 1982. Wind movement within canopies. In J. L. Hatfield and I. J. Thomason (eds.). Biometeorology in Integrated Pest Management. Academic Press, Orlando, Florida. pp. 17-41.
109. Siddall, J., and C. M. Olsen. 1976. Pheromones in agriculture - From chemical synthesis to commercial use. In M. Beroza (ed.). Pest Management with Insect Sex Attractants. Amer. Chem. Soc. Symp. Series. 23:88-98
110. Snow, J. W. Peachtree borer and lesser peachtree borer control in the United States. In R. Ridgway, R. M. Silverstein, and M. Inscoe (eds.). Practical Applications of Insect Pheromones and Other Attractants. Marcel Dekker, New York, New York. In Press.
111. Stanley, B. H., H. E. Hummel, and W. G. Ruesink. 1985. Estimating maximum horizontal area of pheromone plumes. J. Chem. Ecol. 11:1129-1146.
112. Sternlicht, M. 1982. Bionomics of *Prays citri* (Lepidoptera: Yponomeutidae) and their use in a model of control by male mass trapping. Ecological Entomol. 7:207-216.
113. Sternlicht, M. 1986. Reassessment of pest control with pheromones in Israel and abroad (Inaugural talk prior to a discussion). Phytoparasitica 14(1):63-71.
114. Stockwin, W. 1988. Pheromone control works. Western Fruit Grower 108(1):8-9.
115. Suckling, D. M., D. R. Penman, R. B. Chapman, and C. H. Wearing. 1985. Pheromone use in insecticide resistance surveys of light-brown apple moths (Lepidoptera: Tortricidae). J. Econ. Entomol. 78:204-207.
116. Swaby, J. A., G. E. Daterman, and L. L. Sower. 1987. Mating behaviour of douglas-fir tussock moth, *Orgyia pseudotsugata* (Lepidoptera: Lymantriidae), with special reference to effects of female age. Annals Entomol. Soc. Amer. 80:47-50.
117. Taschenberg, E. F., and W. L. Roelofs. 1978. Male redbanded leafroller moth orientation disruption in vineyards. Environ. Entomol. 7:103-106.
118. Taschenberg, E. F., R. T. Cardé, and W. L. Roelofs. 1974. Sex pheromone mass trapping and mating disruption for control of the redbanded leafroller and grape berry moth in vineyards. Environ. Entomol. 3:239-242.
119. Taylor, A. W. 1982. Field measurements of pheromone vapor distribution. In B. A. Leonhardt and M. Beroza (eds.). Insect Pheromone Technology: Chemistry and Applications. Amer. Chem. Soc. Symp. Ser. 190:193-207.
120. Teich, I., A. Shani, and J. T. Klug. 1985. The role of mass trapping of the Egyptian cotton leafworm (*Spodoptera littoralis*) in its integrated pest control. J. Environ. Sci. Health. Part A: Environ. Sci. Eng. 20(8):943-956.
121. Vickers, R. A., G. H. L. Rothschild, and E. L. Jones. 1985. Control of the oriental fruit moth, *Cydia molesta* (Busck) (Lepidoptera: Tortricidae), at a district level by mating disruption with synthetic female pheromone. Bull. Entomol. Res. 75:625-634.
122. Wall, C. 1984. The exploitation of insect communication by man - fact or fantasy? In T. Lewis (ed.). Insect Communication. Academic Press, Orlando, Florida. pp. 379-400.
123. Wall, C., and J. N. Perry. 1982. The behaviour of moths responding to pheromone sources in the field: a basis for discussion. In Les mediateurs chimiques agissant sur le comportement des insectes. Symp. Int. Versailles 16-20 Nov. 1981. INRA Publ. #7 1982. pp. 171-188.
124. Wall, C., and J. N. Perry. 1987. Range of action of moth sex-attractant sources. Entomologia Experimentalis et Applicata 44:5-14.
125. Weakley, C. V., P. A. Kirsch, and R. E. Rice. 1987. Control of oriental fruit moth by mating disruption. California Agriculture 41(5):7-8.
126. Wearing, C. H. 1988. Evaluating the IPM implementation process. Annual Rev. Entomol. 33:17-38.
127. Westigard, P. H. 1973. Pest status of insects and mites in southern Oregon. J. Econ. Entomol. 66:227-232.
128. Westigard, P. H., and H. R. Moffit. 1984. Natural control of the pear psylla (Homoptera: Psyllidae): Impact of mating disruption with the sex pheromone for control of the codling moth (Lepidoptera: Tortricidae). J Econ. Entomol. 77:1520-1523.
129. Wheeler, J. W., and R. M. Duffield. 1988. Pheromones of Hymenoptera and Isoptera. In E. D. Morgan and N. B. Mandava (eds.). CRC Handbook of Natural Pesticides, Vol. IV: Pheromones, Part B. CRC Press, Boca Raton, Florida. pp. 59-206.
130. Wright, R. H. 1964a. Insect control by non-toxic means. Science 144:487.
131. Wright, R. H. 1964b. After pesticides - what? Nature 204:121-125.
132. Wright, R. H. 1965. Finding metarchons for pest control. Nature 207:103-104.
133. Zalom, F. G., M. A. Hoy, L. T. Wilson, and J. M. Smilanick. 1984. Sampling mites in almonds: presence-absence sequential sampling for Tetranychus mite species. Hilgardia 52(7):14-24.
134. Zalom, F. G., K. Klonsky, and W. W. Barnett. 1987. Evaluation of California's almond IPM program. U.C. IPM Publication 6. IPM Manual Group, Davis, California. 33 pp.
135. Zwick, R. W., and G. J. Fields. 1978. Field and laboratory evaluations of fenvelerate against several insect and mite pests of apple and pear in Oregon. J. Econ. Entomol. 71:793-796.

World Watch magazine, new in 1988 from Worldwatch Institute, carries regular articles on the sustainability of agriculture in a global context. "The Vulnerability of Oil," in the March/April 1988 issue, argues for the development of less energy-intensive food production technologies. These include reduced tillage, recycling of human waste back into usable forms, raising the efficiency of irrigation, and green manure rotations, says Worldwatch President Lester Brown. The bi-monthly magazine is $20/year from Worldwatch Institute, 1776 Massachusetts Avenue, NW, Washington, DC 20036.

Biological control of soilborne plant pathogens

Robert D. Lumsden and George C. Papavizas

Abstract. *Soilborne plant pathogens cause major economic losses in agricultural crops, and the present methods for control of diseases brought about by these pathogens are inadequate. Alternatives are also needed to substitute for the use of chemical fungicides. Many of these are known to induce tumors in experimental animals and are thus regarded by some investigators as potential human carcinogens when present as residues in food and water. In addition, such alternative control measures are needed because of the potential threat of development of resistance to fungicides, especially systemic fungicides, by fungal plant pathogens, and because of nontarget side effects on other plant pathogens and on beneficial microorganisms. Alternative disease control is sometimes possible through development of crop plants resistant to disease. Unfortunately, however, resistance is lacking or not available for many diseases caused by soilborne plant pathogens. Another biological means of controlling disease which is presently gaining much attention is biological control. Several systems of biological control are presently being explored and may be developed in a few years into reliable alternatives to conventional chemical control methods. The use of the mycoparasite* Sporidesmium sclerotivorum, *for example, against several diseases caused by* Sclerotinia *species is promising.* Talaromyces flavus *may in the future be exploited for use against several wilt diseases caused by* Verticillium dahliae. *Finally, practical control of several diseases caused by* Pythium *spp.,* Rhizoctonia solani, and Sclerotium rolfsii *may eventually become possible through the use of* Trichoderma *spp. and* Gliocladium virens. *Development of these biological control systems will require much additional research directed toward a better understanding of the basic biology and mechanisms of action of beneficial fungi against plant pathogens. In addition, extensive cooperation will be required among research scientists, governmental agencies responsible for regulating the use of pest control systems, and most importantly, private industry to develop biological control agents for the market and to coordinate acceptance and use by producers and acceptance by consumers.*

Key words: mycoparasites, Sporidesmium, Talaromyces flavus, Trichoderma, Gliocladium, root pathogens, Sclerotinia, Verticillium, Pythium, Rhizoctonia, Sclerotium.

Introduction

Soilborne plant pathogens cause large and economically serious losses to agricultural crops the world over. They inflict damage in the form of root rot, damping-off diseases, blights, fruit decay, and wilts, and cause damage in almost all horticultural and field crops. The extent of the damage is not precisely known, but it is estimated to be at least $4 billion in annual losses to U.S. crops. These loss estimates do not include the added costs of applying chemical fungicides for those disease problems for which fungicides are available.

The substantial loss to agricultural crops justifies a judgment of need for new and improved measures to combat soilborne pathogens. In addition to the costs, there is a critical need to devise alternative disease control measures to replace or supplement chemical fungicides.

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Critical reasons for developing alternative disease control measures

Most important among the reasons for seeking alternative measures for control of soilborne plant pathogens to substitute for the use of chemical fungicides is the need to reduce or eliminate the hazards to health they cause in food and water. Chemical pesticides, especially if used indiscriminately, may contaminate the environment. Examples include persistence of undesirable chemicals in ground water (Hallberg, 1987), direct toxicity of heavy metals (Huisingh, 1974), and suspected carcinogenic risk (Tangley, 1987). The latter hazard is very critical for fungicides. A significant number of all pesticides used today are considered to have a potentiality to stimulate tumor formation, and 90 percent of all fungicides are suspects in this category (Tangley, 1987). For this reason, a large number of commonly used fungicides are under review by the U.S. Environmental Protection Agency. Several of these are currently the primary means of controlling (or partially controlling) several soilborne plant pathogens and the diseases they cause.

Many important plant diseases cannot at present be satisfactorily controlled by chemical means. Among these is the important Verticillium wilt of many agricultural crops and specifically of potato. The pathogen, *Verticillium dahliae*, is the primary cause of the complex early dying disease of potato (Rowe et al., 1987). Partial control of this disease can be achieved by cultural means, by use of tolerant varieties, and, as a last resort, by soil fumigation with costly and toxic broad spectrum chemicals. Although not presently available, an effective primary control measure is needed for this disease. An alternative control is not the question to be considered since an acceptable method is not presently avail-

able. In addition, some field crops, such as cotton, soybean and corn, are low-value crops for which many chemical control measures are too expensive and thus impractical. Alternative means of disease control are needed for these crops, which are otherwise unprotected because of the expense. More economical means of disease control are therefore needed.

In recent years, certain fungicides have been found to induce resistance to their action in some soilborne plant pathogens (Dekker, 1976). The acquired resistance to fungicides by fungi normally sensitive to their action results in forms of pathogens with decreased sensitivity. The resistance may be genetically based or a physiological adaptation. Conversion of pentachloronitrobenzene (PCNB) to a derivative to which *Fusarium oxyporum* f.sp. *lycopersici* is less sensitive offers one example (Dekker, 1976). Other examples include acquired resistance of *Verticillium dahliae* to benomyl, *Rhizoctonia solani* to PCNB, *Sclerotium cepivorum* to dichloran, *Sclerotium rolfsii* to chlorinated nitrobenzene (Dekker, 1976), and *Pythium* spp. to metalaxyl (Gold and Stanghellini, 1985).

Not only are direct target fungal pathogens a problem when resistance is developed, but nontarget fungi may also be affected. The important pathogen *Sclerotinia minor* has in recent years developed into a major problem on peanuts in the southeastern U.S. The fungicide chlorothalonil is used extensively for control of peanut leafspot diseases. With extensive use of this fungicide, it was discovered that the incidence of Sclerotinia blight of peanut was greater than had been noticed previously. Inoculum of *S. minor* produced larger stem lesions on peanut in the presence of 0.2 - 0.4 μg/ml of chlorothalonil than in its absence (Hau and Beute, 1983). Such nontarget effects may disrupt the existing ecosystem and result in altered levels of disease severity or incidence of disease. Other fungicides, including PCNB and benomyl, have also shown nontarget side effects (Hau and Beute, 1983).

Plant resistance or immunity to soilborne pathogens is ultimately the best means of controlling diseases. However, most soilborne plant pathogens cannot be controlled in this way because of the lack of plant resistance. In the future, as biotechnology and genetic engineering techniques become available, this form of biological manipulation of crop genetic makeup will possibly be more feasible than at present.

Another biological means of disease control is increasingly gaining prominence in agricultural research. Biological control or biocontrol is becoming more and more a feasible alternative to chemical control. The current environmental, economic and political pressures mentioned above give impetus to this emerging area of biotechnological research (Cook and Baker, 1984; Papavizas, 1981; Papavizas and Lumsden, 1982). The Biocontrol of Plant Diseases Laboratory at the Agricultural Research Service's Beltsville Agricultural Research Center has played a prominent role in research in this area for several years. The following examples of biocontrol studied in our laboratory may serve as examples of how these emerging technologies have potential as alternative means of control of soilborne plant pathogens.

Emerging technologies for biocontrol of soilborne plant pathogens

Mycoparasitism, the phenomenon in which one fungus parasitizes the mycelium and propagules (sclerotia, oospores, conidia, chlamydospores) of another has been studied extensively, but primarily *in vitro*. Because it has been difficult to demonstrate in nature, the phenomenon has received limited attention as a mechanism of biological control of plant diseases (Ayers and Adams, 1981). Many investigators have concluded that mycoparasitism does not occur to an appreciable extent in nature (Boosalis, 1964).

Ten years ago, scientists in our laboratory discovered an unusual dematiaceous hyphomycete on sclerotia of *Sclerotinia minor*, an economically important pathogen of lettuce and other economic crops. This mycoparasite, described as *Sporidesmium sclerotivorum* (Uecker et al., 1978), was shown to parasitize living, but not autoclaved sclerotia of *S. minor* and other sclerotial fungi in natural soil and *in vitro* (Ayers and Adams, 1979). The newly described mycoparasite was later detected in soils from many areas in the United States and the world (Adams and Ayers, 1981, 1985). Darkly colored macroconidia of *S. sclerotivorum* germinate within 3 days in soil adjacent to sclerotia of *S. minor* and grow through soil from one sclerotium to another, producing many new spores along a network of hyphae through the soil mass. The beneficial fungus is not an obligate parasite of sclerotia (Ayers et al., 1981). However, it has exacting nutritional requirements for growth and sporulation. It is deficient in thiamine and biotin and grows best in media containing glutamine or casamino acids (U.S. Patent No. 4,246,258).

In soil, the mycoparasite *S. sclerotivorum* attacks and destroys sclerotia of *Sclerotinia* spp., *Sclerotium cepivorum* (the onion white rot pathogen), and *Botrytis* spp., but not those of *Sclerotium rolfsii* (Ayers and Adams, 1981). It was also found that *S. sclerotivorum* can bring about a natural decline of sclerotia of *S. sclerotiorum*, and *S. cepivorum* and appreciable disease reduction in a number of production fields (Adams and Ayers, 1982). One application of the beneficial mycoparasite to field plots in May, 1978 at Beltsville reduced the population of *S. minor* by 94 percent in 6 months and provided control of lettuce drop in two consecutive crops, i.e. 63 percent to 83 percent in 1979 and 65 percent and 82 percent control in 1980, without further treatment of the soil. A recent field test at Beltsville with reduced amounts of *S. sclerotivorum* showed that 22.5 kg/ha reduced lettuce drop by 36 percent (Adams, unpublished). This is the best documented case of biological control by a mycoparasite in the field.

Mycoparasites are not the only microorganisms that can bring about biological control of plant diseases. A soil fungus, *Talaromyces flavus* (teliomorph of *Penicillium dangeardii*), isolated by a scientist in our laboratory from sclerotia of *S. minor* decaying in natural soil, is

capable of reducing wilt, an important disease on many plants incited by the soilborne pathogen, *Verticillium dahliae*. This pathogen is especially destructive on eggplants, alfalfa, cotton, potatoes, sunflower, maple and olive trees, hops, mint, pistachio, and other plants. As stated above, no economically practical control is known for the disease in most of the hosts of this wilt pathogen. Eggplant seedlings treated with *T. flavus* by applying ascospores to the greenhouse transplanting mix before moving the seedlings to the field developed 67 percent to 72 percent less Verticillium wilt than controls (Marois et al., 1982). Field applications of this beneficial fungus, together with sublethal amounts of a soil fumigant (65 l/ha instead of 280 of Telone C 17), provided as good control of wilt as the full, recommended rate of the broad spectrum pesticide alone. The *T. flavus* treatment also increased eggplant fruit yield by 75 percent and 22 percent in a field in New Jersey and Maryland, respectively (Marois et al., 1982). Early dying disease caused by *V. dahliae* is a limiting factor in potato production, causing over $50 million losses annually in the United States alone. The beneficial fungus, added to potato seedpieces before planting as dry fermentor biomass in talc, also increased potato yield by about 12 percent and 21 percent, respectively, in *V. dahliae*-infested fields in Canada and Idaho (Fravel, unpublished). *T. flavus*, whose mechanism of action against *V. dahliae* has recently been unravelled by scientists at Beltsville (Kim et al., 1988), is now being tested for the control of Verticillium wilt of potato, hops, cotton, olive trees, and other crops in the United States, Canada, and Europe.

We have recently shown that it is possible to use inexpensive and readily available liquid media to produce large amounts of viable biomass of several potential biocontrol fungi (*Gliocladium*, *Trichoderma*, *Talaromyces*, *Laetisaria*) with a deep-tank fermentation system simulating large-scale industrial production (Papavizas et al., 1984). This system has been adopted by at least two commercial companies in the United States. We also developed delivery technology involving encapsulation of fungal or bacterial biomass in sodium alginate capsules that react with certain metal cations to form gells (Fravel, et al., 1985; Lewis and Papavizas, 1985) (U.S. Patent No. 4,668,512 dated 5/26/87; U.S. Patent 4,724,147 dated 2/9/88).

In a screening test using fermentor biomass as a dust or incorporated in pellets, we showed that of 250 strains and 34 mutants of *Gliocladium* and *Trichoderma*, two strains of *G. virens* (G1-3, G1-21) and two strains of *T. harzianum* (Th-84, Th-87) reduced damping-off and seedling blight of bean caused by the important and widespread soilborne pathogen, *Sclerotium rolfsii* by 40 percent to 80 percent (Papavizas, unpublished). Disease reduction was as effective as that obtained by recommended fungicides. Also, fermentor biomass of these strains, applied to potato seedpieces as dusts, appreciably reduced black scurf and stem canker caused in the field by *Rhizoctonia solani* (Beagle-Ristaino and Papavizas, 1985). Strain G1-21 increased potato yield by 23 percent in Idaho.

This same strain of *G. virens*, G1-21, has been examined closely as a biological control agent for simultaneous protection of greenhouse-grown bedding plants for use against damping-off diseases caused by *Pythium ultimum* and *Rhizoctonia solani* (Lumsden and Locke, 1989, in press). Disease control was effective in widely used soilless mixes in greenhouse production of bedding plants. Although this mix originally is free of the damping-off pathogens which can cause extensive losses in seedling production, it is often contaminated from external sources such as nearby soil or contaminated water supplies. Growers routinely treat greenhouse soils with several fungicides to control these diseases, a practice that contributes to added production costs and environmental pollution. Pelleted formulations of *G. virens* formed from sodium alginate (Lewis and Papavizas, 1985) have been shown to control both pathogens over an extended time period of several months and to store on the shelf for equal periods of time. Eventual use of *G. virens* for control of damping-off and other important soilborne diseases is envisioned.

Conclusions

Biological control technologies offer an exciting, promising, new alternative approach to chemical control of soilborne plant pathogens. To date, however, limited success has been realized and no commercially available products have been developed in the U.S. We do have several candidate fungal and bacterial antagonists to soilborne plant pathogens that, with continued research and perseverance, may be developed in a few years. Continued research in the following areas will help to expedite the reaching of this objective.

1. Evaluate strains of biocontrol fungi and bacteria to select superior strains for most efficaceous control. Continue searching for new species and strains of known species in agricultural systems where disease control naturally occurs.

2. Develop new formulations and systems for delivery of biocontrol agents. Attempt use of combinations of compatible types of biocontrol microorganisms.

3. Increase knowledge of the basic biology of known biocontrol agents and plant pathogens, including their ecology, physiology, biochemistry and genetics. Unravel mechanisms of biocontrol to better apply biocontrol agents in intelligent, sophisticated approaches, including genetic manipulation or bioengineering for enhanced performance.

4. Encourage and develop close cooperation and mutually beneficial programs with private industry to develop improved biocontrol formulations which are economically feasible and efficaceous against multiple disease problems. Cooperate with appropriate governmental agencies to obtain data on toxicology and environmental safety and eventual clearance for use.

5. Develop integrated pest management (IPM) systems to include biological control, cultural practices, disease resistance, and minimal use of fungicides. This approach will require extensive consideration of the agro-ecosystem and its multiple components. This may ultimately be the most successful system for application of biological control to sustained agricultural systems.

Expanded public and private support in these areas of research will aid in developing the long sought after goals of controlling soilborne plant pathogens in agricultural production systems without environmental destruction and with multiple benefit to industry, farmers, and consumers alike.

References

1. Adams, P. B., and W. A. Ayers. 1981. *Sporidesmium sclerotivorum*: Distribution and function in natural biological control of sclerotial fungi. Phytopathology 71:90-93.
2. Adams, P. B., and W. A. Ayers. 1982. Biological control of Sclerotinia lettuce drop in the field by *Sporidesmium sclerotivorum*. Phytopathology 72:485-488.
3. Adams, P. B., and W. A. Ayers. 1985. The world distribution of the mycoparasites *Sporidesmium sclerotivorum*, *Teratosperma oligocladum* and *Laterispora brevirama*. Soil Biol. Biochem. 17:583-584.
4. Ayers, W. A., E. A. Barnett, and P. B. Adams. 1981. Germination of macroconidia and growth of *Sporidesmium sclerotivorum* in vitro. Can. J. Microbiol. 27:664-669.
5. Ayers, W. A., and P. B. Adams. 1979. Mycoparasitism of sclerotia of *Sclerotinia* and *Sclerotium* species by *Sporidesmium sclerotivorum*. Can. J. Microbiol. 25:17-23.
6. Ayers, W. A., and P. B. Adams. 1981. Mycoparasitism and its application to biological control of plant diseases. In G. C. Papavizas (ed.). Biological Control in Crop Production. Allanheld, Osmun: Totowa, New Jersey. pp. 91-103.
7. Beagle-Ristaino, J. E., and G. C. Papavizas. 1985. Biological control of Rhizoctonia stem canker and black scurf. Phytopathology 75:560-564.
8. Boosalis, M. G. 1964. Hyperparasitism. Annu. Rev. Phytopathology 2:363-376.
9. Cook, R. J., and K. Baker. 1983. The nature and practice of biological control of plant pathogens. The American Phytopathogical Society Press, St. Paul, Minnesota. 539 pp.
10. Dekker, J. 1976. Acquired resistance to fungicides. Annu. Rev. Phytopathol. 14:405-428.
11. Gold, S. E., and M. E. Stanghellini. 1985. Effects of temperature on Pythium root rot of spinach grown under hydroponic conditions. Phytopathology 75:333-337.
12. Fravel, D. R., J. J. Marois, R. D. Lumsden, and W. J. Connick, Jr. 1985. Encapsulation of potential biocontrol agents in an alginate-clay matrix. Phytopathology 75:774-777.
13. Hallberg, G. R. 1987. Agricultural chemicals in ground water: Extent and implications. American Journal of Alternative Agriculture 2:3-15.
14. Hau, F. C., and M. K. Beute, 1983. Effects of chlorothalonil on the virulence and physiology of a nontargeted pathogen, *Sclerotinia minor*. Phytopathology 73:475-479.
15. Huisingh, D. 1974. Heavy metals: implications for agriculture. Annu. Rev. Phytopathol. 12:375-388.
16. Kim, K. K., D. F. Fravel, and G. C. Papavizas. 1988. Role of glucose oxidase in the biocontrol of *Verticillium dahliae* by *Talaromyces flavus*. Phytopathology 78:488-492.
17. Lewis, J. A., and G. C. Papavizas. 1985. Characteristics of alginate pellets formulated with *Trichoderma* and *gliocladium* and their effect on the proliferation of fungi in soil. Plant Pathology 34:571-577.
18. Lumsden, R. D., and J. C. Locke. 1989. Biological control of *Pythium ultimum* and *Rhizoctonia solani* damping-off with *Gliocladium virens* in soilless mix. Phytopathology 79: In press.
19. Marois, J. J., S. A. Johnson, M. T. Dunn, and G. C. Papavizas. 1982. Biological control of Verticillium wilt of eggplant in the field. Plant Disease 66:1166-1168.
20. Papavizas, G. C. 1981. Biological Control in Crop Production. Beltsville Symposia in Agricultural Research 5. Allanheld, Osmun Publishers, Inc., Totowa, New Jersey 07512.
21. Papavizas, G. C., M. T. Dunn, J. A. Lewis, and J. Beagle-Ristaino. 1984. Liquid fermentation technology for experimental production of biocontrol fungi. Phytopathology 74:1171-1175.
22. Papavizas, G. C., and R. D. Lumsden. 1982. Biological control of soilborne fungal propagules. Annu. Rev. Phytopathol. 18:389-413.
23. Rowe, R. C., J. R. Davis, M. L. Powelson, and D. I. Rouse. 1987. Potato early dying: causal agents and management strategies. Plant Disease 71:482-489.
24. Tangley, L. 1987. Regulating pesticides in food. Bioscience 37:452-456.
25. Uecker, F. A., W. A. Ayers, and P. B. Adams. 1978. A new hyphomycete on sclerotia of *Sclerotia sclerotiorum*. Mycotaxon 7:275-282.

Farm pesticide bill signed by President

Legislation to speed up the safety review of some 600 existing farm pesticides was signed into law by the President on October 25, 1988. The revision of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) calls for reregistration of all previously untested pesticides within nine years. Chemical companies must share with the government the cost of storing suspended and cancelled pesticides and take responsibility for disposal costs. The review program will be funded by fees levied on pesticide manufacturers.

The action remedies the fact that many early pesticides have never been tested by current methods. Although the Environmental Protection Agency has been slowly reviewing these farm chemicals, the agency had admitted that, with the new bill, these reviews would not be completed until well into the 21st century. Previous sessions of Congress have considered these reforms, but failed to reach agreement on a wider range of issues. The bill bypassed controversial matters such as ground water protection from pesticides and allocation of state/federal regulatory powers to gain quick action on the stepped-up review process.

A second look at trap for livestock fly control

In the 1950s, University of Missouri scientists developed an ingenious trap for catching the flies that plague cattle. But when chemicals were developed for fly control, the trap plans fell by the wayside. Today, horn fly resistance to insecticides has led to renewed interest in the trap, reports the Nebraska Sustainable Agriculture Society.

Here's how it operates. The trap is placed so that the animal must walk through it on a regular basis--on the path to water, for example. When an animal walks through, the flies are brushed off and then attracted to sunny areas on the sides. Screens keep the flies from returning to the animal as it leaves the trap. Simple, but perhaps effective.

Nebraska's Center for Rural Affairs is testing the trap on several cooperator farms during the next year as part of their work to develop viable low-input livestock systems. For more information, contact Larry Krcil, Center for Rural Affairs, P.O. Box 736, Hartington, NE 68739.

Implementation of biological control

Joop C. van Lenteren

Abstract. *The number of species of insect pests, estimated to be maximally 10,000 worldwide, forms only a small part of the millions of species of plant-eating insects. Chemical pest control is becoming increasingly difficult and objectionable in terms of environmental contamination so that other methods of pest control need to be developed. One of the best alternatives is biological control. Natural and inoculative biological control has already proven successful against a variety of pests over large areas. One is inclined to forget, however, how successful a biological control program has been as soon as the pest problem has been solved. Other types of biological control involving the regular introduction or augmentation of natural enemies are better known, although these have been applied on a much smaller scale; a survey of the present-day application of these latter types of biological control is presented here. Phases in the implementation of biological control are illustrated and needed future developments in research are discussed. The main limitation on the development of biological control is not the research, since natural enemies are easier found and with a much lower investment than new chemical pesticides, but rather the attitudes held by growers and disinterest on the part of industry, policy-makers, and politicians. The first priority for those concerned with the development and application of safer pest control should, therefore, be to change the perceptions that these other groups have of biological control.*

Key words: insect biological control, inoculative release, inundative release, vegetables, greenhouses, grower attitudes

Introduction

The number of animal species is estimated to be about 50 million, only 1.7 million of which have been described to date. About 75 percent of all animal species are believed to be insects. Insects eating green plants are thought to comprise about half of the total number of insect species (Strong et al., 1984). Most species of herbivores occur in the orders Coleoptera (beetles) and Lepidoptera (butterflies and moths). Although the number of species of herbivores among insects is very large, the number of species regarded as pests is small; estimates vary between 500 and 10,000. Why is this number so small?

Ecologists and applied entomologists have ample evidence relevant to the just-stated question: natural enemies are able to keep potential pest species at densities so low that no serious damage is caused (e.g. Huffaker and Messenger, 1976). This phenomenon is known as natural control. It is important to realize its existence, because we might thereby learn more from nature's way of pest control than we have in the past. Many alternatives for chemical pest control are possible; most of them have been exploited only superficially (DeBach, 1974; van Lenteren, 1987). In the past, the impulse behind searching for non-agchemical methods of pest control has consisted mainly of recognition of the risks of chemicals for the environment and human health (Carson, 1962; Rudd, 1964). With increasing pesticide resistance, increasing costs of pesticides, and the present difficulties in developing new and effective chemical pesticides (Metcalf, 1980; Dover and Croft, 1984); however, there are presently also strong signals from agriculture itself that the time has come to change from a policy of opportunism in pest control, in which problems are allowed to develop and solutions in the field of chemical control are hoped for, while danger signals are being neglected, to a policy of vigorous development of biologically based pest control (van Lenteren, 1986b), a promising alternative to chemical methods. Biological control tactics against some pests are usually combined with other methods against different pests in the so-called Integrated Pest Management (IPM) programs (Stern et al., 1959; Metcalf and Luckmann, 1982).

Types of biological control

Several types of biological control are distinguished. We will describe here a classification based on the way in which natural enemies are used in diferent agricultural systems.

In the **inoculative release method**, beneficial organisms are collected in an exploration area and introduced into the area where the pest occurs. Only a limited number of beneficials is released; the aim is long-term control. The method is generally applied in orchard and forest ecosystems where a continuing survival of natural enemies can be confidently expected. Biological control of cottony cushion scale, described later here, is an example of the inoculative release method. See DeBach (1974) and Huffaker and Messenger (1976) for more examples. This method is also known as "classical biological control."

In the **inundative release method**, beneficials are collected, mass-reared, and periodically released in large numbers to obtain immediate control, thus are used as biotic insecticides. This method is applied against pests with one or two generations in annual crops. A well-known

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example is the application of the parasitic wasp *Trichogramma evanescens* against the European cornborer *Ostrinia nubilalis* in Europe (Hassan, 1981). Additional examples are described by Ridgway and Vinson (1977).

In the **seasonal inoculative release method**, natural enemies are collected, mass-reared, and released seasonally in annual crops against pests with many generations. A relatively large number of natural enemies is released to obtain both an immediate control effect and a build-up of a natural enemy population for control later during the season. This method is similar to the inoculative method and is applied when the cultural method used with a crop prevents the effects of a single release from lasting many years. The method is used extensively in greenhouses, in which crops are removed, together with the pests and their natural enemies, at the end of the growing season. For examples, see van Lenteren and Woets (1988).

Current use of biological control

The area and number of kinds of pests under natural control are large, and the extent to which natural control works can only be understood from situations in which man interferes with nature and natural control is upset. Abundant evidence for the role of natural control comes from experiences with chemical control; chemical control can strongly reduce or locally eradicate natural enemies and, therefore, lead to resurgence of the target pests and to the creation of new pests (e.g. DeBach, 1964, 1974).

The area under inoculative or classical biological control is difficult to estimate. Results obtained with this type of biological control are soon forgotten because no repeated, weekly to yearly action is needed to keep pest numbers down. The important and continuous role which the introduced ladybird beetle *Rodolia cardinalis* has played since 1888 in California, and later in many countries all over the world, to keep the cottony cushion scale, *Icerya purchasi*, below damage levels was stressed by resurgence of this pest in 1947 as a result of the widespread use of DDT in citrus (Stern et al., 1959). It would be to the benefit of biological control if areas under inoculative biological control were better known. Yearly specification of such data, with economic benefits, would attract the respect needed for this activity.

It is easier to obtain data for those types of biological control in which natural enemies have to be released regularly. Table 1 provides data. These data lead to the conclusion that in Western Europe as well as in North America, where production per unit area is highest, these types of biological control have not been put into practice to any great extent.

I can only judge reliably the success of application of biological control in the above-mentioned countries. Publications from other parts of the world relate to large areas where natural enemies are released. Biological and economical evaluations usually are lacking, however, and the use of biological control is often the only pest control strategy available.

Table 1. Examples of worldwide use of biological control.

crop	area(ha)	pest(s)	beneficial(s)	countries and references
cabbage, tomato sugar beet, cotton cereals, fruit	11,000,000	Lepidoptera butterflies and moth	*Trichogramma* spp	USSR, 1
grain, citrus, deciduous fruit, mulberry, sugar beet, vegetables	10,000,000	many pest species mainly Lepidoptera	15 species mainly *Trichogramma*	USSR, 2
rice, sorghum, millet, corn, cotton forest, sugar cane	2,000,000	Lepidoptera several other pests	*Trichogramma* spp 10 other species	PRC, 3–7
cotton, sugar cane	335,000	Lepidoptera	*Trichogramma* spp	USA, 8–9
citrus	13,000	scales and mealybugs	*Aphytis* spp, *Chrysopa Cryptolaemus* spp	
corn	10,000	*Ostrinia nubilalis* European corn borer	*Trichogramma* spp	A,CH,D,F,I 10
orchards	10,000	*Panonychus ulmi* European red mite	predatory mites	CH,D,F,I,NL 10
		Aculus schlechtendali apple rust mite	predatory mites	
		Stigmella malella apple pygmy moth	*Chrysocharis prodicae*	
		Eriosoma lanigerum woolly aphid	*Aphelinus mali* and earwigs	
greenhouses	2,350	*Trialeurodes vaporariorum* greenhouse whitefly	*Encarsia formosa*	many 11
	5,100	*Tetranychus urticae* two spotted spider mite	*Phytoseiulus persimilis*	many 11
	460	*Liriomyza bryoniae* leafminer	*Dacnusa sibirica*	F,NL,UK 11
		Liriomyza trifolii leafminer	*Diglyphus isaea*	F,NL,UK 11
	1,000	Lepid. caterpillars	*Bacillus thuringiensis*	F,NL,UK 11
	140	*Thrips tabaci*	*Amblyseius cucumeris*	NL 11
p.m. natural control	immense	many	many	worldwide, 12–13
p.m. classical control	vast	many	many	worldwide, 12–13

Countries: USSR = Union of Socialistic Soviet Republics; PRC = Peoples Republic of China; USA = United States of America; A = Austria; CH = Switzerland; D = Federal Republic of Germany; F = France; I = Italy; NL = Netherlands; UK = United Kingdom

References: 1 = Voronin, 1982; 2 = Beglyarov and Smetnik, 1977; 3 = Huffaker, 1977; 4 = Pu, 1984; 5 = Cock, 1985; 6 = Gou Xuegi, 1986; 7 = Li Liying, 1986; 8 = Ridgway and Vinson, 1977; 9 = King et al., 1985; 10 = Anonymous, 1976–1988; 11 = van Lenteren and Woets, 1988; 12 = DeBach, 1964; 13 = Huffaker and Messenger, 1976

Hokkanen (1985) estimated that during the last 100 years some 3000 natural enemy introductions have been made worldwide against arthropod pests and weeds. This has involved more than 1000 species of parasites, predators, pathogens, and herbivores aimed at almost 200 target pest species.

Implementation of biological control

It is rather easy to develop a set of guidelines for implementation of biological control behind a desk. Each practical situation, however, dictates a number of special topics for consideration. Even in a small country like the Netherlands we have had the experience that implementation of biological control in some crops (e.g. vegetables in greenhouses) is much easier than in others (e.g. fruit orchards). This has occurred not only because of differences in culture methods or pest problems, but also because of different attitudes of growers. I will not, therefore, try to present specific guidelines for implementation, but rather list points to be considered on the basis of my experience with development of biological pest control for greenhouse pests.

Technically, implementation of biological control is not different from that of chemical control except for psychological and socio-economic impediments as mentioned later. At the introduction of the first biological control agent in a crop, special attention should be paid to extension; the growers have to reexperience the way in which biological control works and learn to rely on it. For extension workers, the problem is that proper guidance of biological control demands much entomological knowledge and understanding. When growers, extension workers, and researchers agree that the use of a natural enemy is as cheap as chemical control and that production and delivery of beneficials is reliable, biological control can be applied in a way similar to that in chemical control and becomes a normal commercial operation.

Before we in the Netherlands start developing biological control for a new pest, the following questions are considered: Is the pest occurring in a large part of the production area of a crop? Does chemical control of this pest interfere with biological control of other pests in the system? If the answer to both questions is positive, a meeting is organized with researchers, extension workers, producers of natural enemies, and representatives of growers organizations; and questions are discussed on how to attack the new pest problem and in what way to divide the work.

Usually the research starts at a university department with a literature search, followed by the collection of different natural enemies and a first screening. Based on criteria like (a) possible negative effects of the natural enemy on the agro-ecosystem, (b) possibility to develop on/in the pest insect at greenhouse climate conditions, (c) ease of mass rearing, and (d) the maximum rate of population increase (r_m) relative to that of the pest insect, a first selection of candidate species is made. For a discussion of these criteria, see Huffaker and Messenger (1976) and van Lenteren (1986b). Candidates are then tested in experimental greenhouses at local research stations, followed by tests in commercial greenhouses. During this latter phase, the producer of natural enemies develops mass production techniques and methods for transport and introduction of beneficials into the greenhouse. All participants in a project work together with the extension service on an extension program. Progress reports are published regularly in growers journals. This type of cooperative effort has led in the past 25 years to introduction of 9 natural enemies against 12 pests on a large part of our main vegetables grown in greenhouses (up to 90 percent of the total area for certain crops (van Lenteren and Woets, 1988)). Our growers have learned to rely on biological control and now ask for new natural enemies before we can provide them with the necessary information. This enthusiasm can, however, create a new problem, i.e. a too early release of a natural enemy can result in a bad control effect and thus have a negative effect on the reputation of biological control!

Several conditions have to be met before the technical implementation of biological control becomes a success. Biological control agents should be as cheap, as easily available, as reliable, as constant in quality, and as well guided as chemical control agents. They should fit well into the total crop protection program and not be seen as an endeavor separate from other crop protection measures (see below: integrated farming). An important consideration during development of biological control is that for some pests or diseases either selective pesticides or pesticides that can be applied selectively should be available.

The phase of introducing biological control into practice is often neglected. Frequently there is a misconception that a practice or procedure will be adopted if superior to procedures already commonly practiced. Actually, alternative control procedures will be adopted only when they are *perceived* to be better than current methods (Wilson, 1985). Experience in the Netherlands has shown that the amount of application of IPM is strongly related to the activity and attitude of extension personnel. If governmental extension services are weak, biological control will have no chance.

For biological control in greenhouses, the above-mentioned conditions have been met. Furthermore, some additional aspects make use of natural enemies extra attractive: (a) With biological control, there are no phytotoxic effects on young plants, and premature abortion of flowers and fruit does not occur. (b) Release of natural enemies takes less time and is more pleasant than applying chemicals in humid and warm greenhouses. (c) Release usually occurs shortly after the planting period, at which juncture the grower has ample time to check for successful development of natural enemies; thereafter the system is reliable for months with only occasional checks; chemical control requires continuous attention. (d) Chemical control of some of the key pests is difficult or impossible because of pesticide resistance. (e) With biological control, there is no safety period required between application and harvesting fruit; with chemical control one has to wait several days before harvesting is allowed again.

Impediments to implementation

Research

Funding. Results in non-chemical pest control are, of course, dependent in the first instance on the amount of research and development work. Funding of this work is limited, especially if one realizes the complexity of this type of research. Although it is difficult to compare research inputs in chemical and non-chemical control because of limited availability of data, I recently heard the following figures. West Germany's chemical industry spends 200 million DM annually on research for new pesticides, whereas in the same country the Institute for Development of Biological Control Methods has a funding of only 2 million DM per year. Research and development costs in the United States on biological control have been less than 20 million U.S. dollars during the period 1917-1972, i.e. less than half a million dollars per year. Costs for research and development for chemical pesticides in 1973 in the U.S. were 110 million dollars (Sailer, 1976).

Cost-benefit analyses (DeBach, 1974; Huffaker and Messenger, 1976) show that the financial benefits are considerably higher in biological control than in chemical control (cost-benefit ratios of 1 to 30 and 1 to 5 respectively). DeBach (1964, 1974) has emphasized that the level of financial support is positively correlated with success in classical biological control. My experience with inundative and seasonal inoculative types of biological control are similar: proper funding and a stable research situation lead to success.

Orientation of research. Research efforts, as Rothman and Woodhead (1968) showed, tend to be towards the newest approach (e.g. in the sixties toward the pheromones, in the seventies toward the use of models, in the eighties toward genetic engineering). These fashions in IPM do not always result in optimal results. Developments by the "good-old" approaches, such as biological control and host-plant resistance, that have been shown to deliver reliable results with low economic inputs, are at least to some extent hampered by these vogues.

Very often insufficient funding is the only factor mentioned as a primary limitation for implementation. It is my conviction that implementation is most hindered by other constraints, which I will discuss below.

Growers attitudes. Very few grower organizations ask for, or stimulate development of, biological control. Adoption of insecticides occurred rapidly because they allowed the grower to decide when and where to use them. Decision criteria were clear, the method was easily understood, and it was effective. At least in the short run, it reduced labor costs and was a practice he could control and decide on independently of his neighbors, institutions, or agencies. Initially it was a straight-forward technology. In contrast, biological and integrated crop management methods are more complicated because of the requirement for monitoring various pests, integration of different pest control measures, and situation-specific prescriptions. This requires a degree of knowledge and sophistication much above that required by the pesticide technology (Perkins, 1982).

Initiatives for development of biological control programs had and will have to come from researchers and policy-makers. Being unable to control a pest with chemicals is a stronger reason for farmers to change their ideas on biological control than idealogical reasons. We should not reproach the grower with this attitude, because governments legislate the use of chemicals and often state that when chemicals are used as advised they do not contaminate food or the environment and do not harm plants, animals, or humans. If one does not agree with the use of pesticides, the government should be contacted to obtain a change in pesticide legislation policy.

The chemical industry. The industry provides pesticides which are allowed for use by the government's legislation. In general, we can state that any complication in a simple, pure chemical pest control program is considered to be a negative development by the large industries. Biological and natural control, which are regarded as cornerstones of IPM, not only complicate chemical control programs, but they seem to be commercially unattractive as well because of a combination of (a) impossibility of patenting natural enemies, (b) complicated mass production, (c) short shelf-life, (d) specificity, and (e) different and more complicated needs for guidance of growers (van Lenteren, 1986b). Industry shows at present some interest in microbial pesticides, as they are much easier to produce and store than parasitic and predatory insects. This causes special problems because this specific interest for microbial pesticides might generate the idea that they are potentially better natural enemies than predators and parasites, and this is certainly not the case.

I am convinced that chemical companies will not start the production of materials other than broad spectrum pesticides on their own initiative unless the use of those pesticides is prohibited or when pest organisms develop resistance, but time is on our side. We cannot blame the companies for this attitude because their goal is the making of profit. It is the governmental bodies that have to take the lead here. They are, in fact, the only ones able to change the pest control picture through measures making chemical control less attractive (legislation, registration, tax, side-effect labeling, etc.) and through stimulating other control methods, i.e. funding research, but above all teaching on all levels and improvement of the extension service.

Socio-economics. The availability of cheap and effective chemicals has resulted in a lowering of economic damage thresholds, which makes the application of other-than-chemical control more difficult than before these chemicals were on the market and more damage had to be tolerated. The costs for pest control are on the average very low and amount to only 3 percent of the investment for producing a crop. Calendar and insurance spraying are therefore no exceptions. An alternative control method has to be considerably cheaper or more attractive before a farmer will consider its use (see above under growers attitudes).

Although biological control is often

not more expensive than chemical control, the degree of knowledge required makes acceptance of more complicated IPM programs difficult for the farmer. Biological control in greenhouses was accepted so fast and is applied on such a large scale mainly because of lower costs, i.e. labor saving and ease of application, compared with chemical control (Ramakers, 1982; van Lenteren and Woets, 1988). IPM in orchards in the Netherlands is nowadays as cheap as chemical control, but because of a more complicated total program, implementation is slower than in greenhouses.

In biological control, environmental and social costs are lower, but this is a long-term advantage and of low actual value to the farmer (Gruys, 1982). Changes in crop-protection strategies can therefore be realized only effectively through governmental measures as long as they do not lead to an excessive increase in pest control costs in the short term.

Since the general nature of the basic barriers is lack of confidence, knowledge, and experience, the only way to overcome them is to install demonstrations on commercial farms showing potentials of IPM, in combination with extensive coverage of this work in professional and non-professional journals. Gruys (1982) describes requirements for such demonstration farms. The most important are:

-- It should be a cooperative effort of farmers, extension officers, pesticide industry, and governmental agencies and research.

-- It should involve the public and students of agricultural schools and universities as apprentices.

-- It should compensate farmers for any extra costs of control and supply insurance against any failures.

Very few demonstration projects exist presently, and these only partly fulfill these requirements.

Future research

Pre-introductory selection and evaluation of natural enemies

I estimate that some 2500-5000 species have been tested for use in biological control programs. Of these, 519 species have established after introduction (J. K. Waage, pers. comm.), of which 270 species have led to partial (100 species), substantial (100 species) or complete (70 species) control. More than 80 percent of the successful natural enemies are parasites, the remainder are predators (17 percent) and pathogens (1 percent) (DeBach, 1964; Laing and Hamai, 1976; Clausen, 1978).

Most natural enemies have been found through trial and error. Many researchers have thought about ways of optimizing the pre-introductory studies so as to increase the predictability of success before introductions are made. We should keep in mind, however, that the success ratio and economic evaluations are both strongly in favor of biological control when compared with chemical control, even with the trial and error method. I can best summarize the present-day extremes in point of view related to natural enemy testing by quoting Ehler (1982): "(1) conduct pre-introduction studies to determine the 'best' species or complex of species to introduce; or (2) conduct minimal pre-introduction studies and simply release all suitable natural enemies and hope that the 'best' species or combination of species will be sorted out in the field."

What does this mean for the biological control practitioner whose aim is to obtain a pest density below the economic threshold? At the moment, we can conclude only that different theories produce different or even conflicting advice on selection criteria. The practitioner is not only confused but may also delay application of biological control measures while he is determining the wrong criteria. Thus, Way's (1973) opinion is still applicable: "At present too few research workers are able to bridge the gap between pest-control practitioners who are blinded by short-term needs, and theoreticians or pure ecologists who have inadequate appreciation of practical realities."

For a discussion on which criteria might be used in pre-introductory evaluation programs and for a procedure for selecting natural enemies, I refer to DeBach (1964, 1974), Huffaker and Messenger (1976), Ridgway and Vinson (1977), and van Lenteren (1986a,b). In the last two articles, examples are given on how we selected successfully new natural enemies for use in glasshouses.

Mass production, quality control, storage, shipment and release of natural enemies

Development of mass-rearing techniques is necessary for programs with a short-term control effect. Only some 15 natural enemies are presently reared on a large scale (King and Morrison, 1984; van Lenteren and Woets, 1988). The technology for rearing natural enemies on unnatural hosts and host plants, or on artificial diets, is little developed. Physiological, ethological, ecological, and genetic problems hamper developments. Conflicting requirements for natural enemies in mass-rearing and field performance, combined with risks from rearing on artificial hosts or diets, make good quality control a necessity. Although quality control methods are available, they are seldom applied (King and Leppla, 1984). Innovations in long-term storage (through diapause), and shipment and release methods may lead to a further reduction in costs of biological control, thereby making it easier and economically more attractive to apply.

Genetic improvement of natural enemies

Research on genetic improvement in hymenopterous parasites has been summarized by Roush (1979). Successes have been obtained in the laboratory but no one has yet been able to demonstrate increased effectiveness of parasites in the field. The situation seems to be different with respect to predators, particularly for predatory mites, as Hoy has shown us earlier in this symposium.

The most popular trait for genetic improvement in biological control seems to be the development of pesticide resistance in natural enemies. Increased pesticide resistance has been found for natural enemies (Hoy, this symposium), but I doubt that this benefits biological

control in the long term. The dilemma here is whether the optimal strategy for a biological control research worker is either to search for new natural enemy species (which are abundantly available) for a pest that still has to be controlled with chemicals, or to develop pesticide resistance in some of the already used natural enemies. Although I believe genetic improvement to be an attractive and important field of study, I am on the other hand astonished by the indiscriminate enthusiasm which exists for this technique. It might even interfere with development of biological control when research funds are redirected from the search and evaluation of new natural enemies to genetic improvement.

Computer models

Despite the considerable effort devoted to use of modeling techniques in crop protection, the use of models in crop protection decision-making is very limited. Still, it is only with system analysis and modeling that complex crop protection measures can be evaluated. An analysis of the use of models in crop protection by Jeger and Tamsett (1983) shows that few models are being developed to practical ends in crop protection: "Those which have found some use are mainly for forecasting individual events within the epidemic...There are few examples...of comprehensive explanatory models that are developed, evaluated, and subsequently simplified to some more practical form." As an example in this last category, I can mention the EPIPRE (EPIdemics PREvention) program, used for supervised disease control by wheat farmers (Zadoks, 1984).

Farming systems

One of the main technical short-falls in the development of biological control in arable crops has been in implementation of truly integrated control programs in which entomologists, plant pathologists, and weed specialists work together with agronomists and plant breeders. A farming systems approach is considered necessary, therefore, to study crop protection in relation to other system components such as fertilization, cultivation, or rotation (Vereijken et al., 1986) and to evaluate farm economics. Success with IPM (or better with integrated farming) can be obtained only when there is appreciation for more than quantity and quality of production and for the economic profits. At the same time, integrated farming should be a realistic instead of only an idealistic approach.

Farm economics is the central point in farming systems, and not plant protection (Vereijken et al., 1986). In integrated farming, ecological and environmental effects, such as pollution of soil and water by pesticides, can be minimized. In general, integrated farming takes more completely into account the various impacts on ecosystems (preservation of flora and fauna, quality and diversity of landscape, and need of energy and non-renewable resources) and societal considerations (employment, public health and well-being of persons associated with agriculture) than is the case with conventional farming (Vereijken et al., 1986). Although the objective of obtaining a better balance between the various influences, based on a growing awareness of problems caused by conventional farming, is frequently expressed, realization is difficult to achieve so long as politicians and policymakers merely pay lip service to integrated farming and do not provide the means for its accomplishment.

In Western Europe, national integrated farming systems have been put in place only at Lautenbach in the Federal Republic of Germany and at Nagele in the Netherlands. The aim is to investigate the relative technical and economical potential of low-input systems (with great environmental benefits) as compared with those in high-input systems (with low environmental benefits). More countries should start such programs to provide reliable cost-benefit analyses, the ultimate data on which different farming systems can be evaluated. An integrated farming system is: "a coherent farm unit or set of units which relies basically on cultural and biological inputs, with chemicals as integrated supplements" (Vereijken et al., 1986). The main aims are: "to minimize inputs of non-renewable resources and to provide a better balance between adequate production of yields and farm income on the one hand and ecological, environmental, and sociological aims on the other. All these considerations must be compatible with cost effectiveness." An important new element in such integrated farming studies is that they might provide a long-term alternative for the present-day farming systems, which lead to overproduction and environmental problems.

A description of such a program of analyses can be found in Vereijken et al. (1986). Ideally, three systems should be compared:

1. high-input systems, exclusively aimed at maximizing short-term yields and profits
2. integrated systems, aimed at optimum yields, in terms of economics, long-term stability, and environmental quality
3. low-input systems in which effort is aimed at optimum use of natural elements and processes and in which synthetic inputs are as low as possible (e.g. biodynamic and macrobiotic farming).

The practices which can be manipulated in such programs are crop rotation, cultivation, fertilization, pesticide use, cultural control measures, biological control, and other alternatives for conventional chemical control.

Research on two demonstration-research farms, although started only recently, has shown the possibility of economically successful integrated farming and has led to many new cultural practices. The practical results obtained in one of these projects at Nagele, the Netherlands, after 5 years, are summarized in Table 2. Integrated control gives the best economical results, but conventional farming is not far behind; biodynamic farming is far behind. The generally lower physical yields on the integrated system were compensated for by cost reduction as a result of the lower input of pesticides and fertilizers. Integrated farming requires a higher input of knowledge than conventional farming and requires practical experience on the part of the farmer.

Table 2. Overall farm inputs (labour, fertilizer, pesticides) and economic results of three farming systems over the years 1982–1984. The three systems are compared at one farm of circa 60 hectares in Nagele, the Netherlands. On the conventional and integrated plots the same kind of crops are grown. One Dutch guilder is about 0.5 US dollar (from Vereijken 1986).

	conventional	integrated	biodynamic
farm size (ha)	17	17	22
labour (person/year)	0.5	0.6	1.9
fertilizer (kg/ha)	540	320	370
pesticides (kg a.i./ha)	60	3	0
total costs (x Fl. 1000)	131.2	118.8	249.9
total returns (x Fl. 1000)	127.8	118.2	156.7
net surplus (x Fl. 1000)	−3.4	−0.6	−93.2

Conclusions

Biological and integrated pest control can be economically profitable endeavors. Many natural enemies await discovery. The rate at which natural enemies are found is determined by the financial inputs into research and development.

Because the main advantages of biological control are at the social and environmental level and on the long term, rather than purely at the private and short-term economic levels, governmental agencies should take the lead in initiating and implementing demonstration projects.

Stimulation of developments in biological and integrated pest management as aspects of integrated farming will have to be found mainly in coordination of research and application, and in an effective introduction policy. Greatly increased funding in this field on the short term is an illusion.

It is an essential prerequisite that *all* participants, including extension workers and farmers, in an IPM project should be receptive to new developments and willing to implement them. If governmental bodies do not support implementation of IPM, efforts of researchers should be directed first and only at a change of policy at high levels.

A goal-oriented, long-term planning of crop protection is necessary on which to base IPM developmental work. With good planning, existing alternative methods can be used to realize a gradual improvement of crop protection. Successful research alone does not guarantee application of IPM. If there are no serious reasons to change, the use of the easy chemical control systems will continue. Directed governmental actions are needed, therefore, to start application of IPM and to reduce the use of pesticides.

Our approach in the Netherlands is to determine whether new methods are applicable within the economic constraints of the farmer, and to demonstrate and explain that these methods will not impair financial returns and will probably be beneficial in the long term to society as a whole (Gruys et al., 1980).

It is several years since the first biological success in the United States was obtained, i.e. control of cottony cushion scale, *Icerya purchasi* Maskell, with the ladybird beetle *Rodolia cardinalis* (Mulsant). Discovery of synthetic chemical pesticides has impeded the development of biological control since the 1940's, but as pesticides are becoming more costly and are increasingly recognized to be harmful to the environment, the future for biological control looks better than ever!

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References

1. Anonymous. 1976-1988. Bulletins of the International Organization for Biological Control, West Palaearctic Regional Section (IOBC/WPRS).
2. Beglyarov, G. A., and A. I. Smetnik. 1977. Seasonal colonization of entomophages in the U.S.S.R. In R. L. Ridgway and S. B. Vinson (eds.). Biological Control by Augmentation of Natural Enemies, Plenum Press, New York, New York, pp. 283-328.
3. Carson, R. 1962. Silent Spring. Houghton Mifflin Co., Boston, Massachusetts, 368 pp.
4. Clausen, C. P. 1978. Introduced Parasites and Predators of Arthropod Pests and Weeds: A World Review. USDA/ARS, Washington, DC, 545 pp.
5. Cock, M. J. W. 1985. The use of parasitoids for augmentative biological control of pests in the People's Republic of China. Biocontrol News and Information 6:213-223.
6. DeBach, P. (ed.). 1964. Biological Control of Insect Pests and Weeds. Chapman and Hall, London, 844 pp.
7. DeBach, P. 1974. Biological Control by Natural Enemies. Cambridge University Press, London, 323 pp.
8. Dover, M., and B. Croft. 1984. Getting Tough: Public Policy and the Management of Pesticide Resistance. World Resources Institute, Study 1, 80 pp.
9. Ehler, L. E. 1982. Foreign exploration in California. Environmental Entomology 11:525-530.
10. Gou Xuegi. 1986. Research and application of Trichogramma in China. Natural Enemies of Insects VIII:52-62.
11. Gruys, P. 1982. Hits and misses. The ecological approach to pest control in orchards. Ent. exp. & appl. 31:70-87.
12. Gruys, P., D. J. de Jong, and H. J. Mandersloot. 1980. Implementation of integrated control in orchards. In A. K. Minks and P. Gruys (eds.). Integrated Control of Insect Pests in the Netherlands. Pudoc, Wageningen, pp. 11-17.
13. Hassan, S. A. 1981. Mass production and utilization of Trichogramma. 2. Four years of successful biological control of the European corn borer. Meded. Fac. Landbouww. Rijksuniv. Gent. 46:417-428.
14. Hokkanen, H. M. T. 1985. Success in classical biological control. CRC Critical Reviews in Plant Sciences 3(1):35-72.
15. Huffaker, C. B. 1977. Augmentation of natural enemies in the Peoples Republic of China. In R. L. Ridgway and S. B. Vinson (eds.). Biological Control by Augmentation of Natural Enemies. Plenum Press, New York, New York, pp. 329-340.
16. Huffaker, C. B., and P. S. Messenger (eds.). 1976. Theory and practice of biological control. Academic Press, New York, New York. 788 pp.
17. Jeger, M. J., and J. Tamsett. 1983. The status of models in crop protection: An analysis using data base systems. Bulletin IOBC/W.P.R.S. 1983/VI/2:57-71.
18. King, E. G., K. R. Hopper, and J. E. Powell. 1985. Analysis of systems for biological control of crop arthropod pests in the U.S. by augmentation of predators and parasites. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, New York, New York, pp. 210-216.
19. King, E. G., and N. C. Leppla (eds.). 1984. Advances and challenges in insect rearing. USDA, ARS, New Orleans, Louisiana. 306 pp.
20. King, E. G., and R. K. Morrison. 1984. Some systems for production of eight entomophagous arthropods. In E. G. King and N. C. Leppla (eds.). Advances and challenges in insect rearing. USDA, ARS, New Orleans, Louisiana, pp. 206-222.
21. Laing, J. E., and J. Hamai. 1976. Biological control of insect pests and weeds by imported parasites, predators and pathogens. In C. B.

Huffaker and P. S. Messenger (eds.). Theory and Practice of Biological Control. Academic Press, New York, New York, pp. 686-743.
22. Li Liying. 1986. Mass production of natural enemies (parasites and predators) of insect pests. Natural Enemies of Insects VII:52-62.
23. Metcalf, R. L. 1980. Changing role of insecticides in crop protection. Annu. Rev. Entomol. 25:219-256.
24. Metcalf, R. L., and W. H. Luckmann (eds.). 1982. Introduction in Integrated Pest Management. Wiley, New York, New York. 577 pp.
25. Perkins, J. H. 1982. Insects, experts, and the insecticide crisis. The quest for new management strategies. Plenum Press, New York, New York. 304 pp. .
26. Pu Zhelong (ed.). 1984. The Principles and Methods of Biological Control of Insect Pests. Scientific Press, Beijing.
27. Ramakers, P. M. J. 1982. Biological control in Dutch glasshouses: Practical applications and progress in research. Proc. Symp. Integrated Crop Protection, CEC, Valence, France, pp. 265-270.
28. Ridgway, R. L., and S. B. Vinson. 1977. Biological control by augmentation of natural enemies. Insect and mite control with parasites and predators. Plenum Press, New York, New York. 480 pp.
29. Rothman, H., and M. Woodhead. 1968. Publication trends in biological control. Nature, London, 220:1053-1054.
30. Roush, R. T. 1979. Genetic improvement of parasites. In M. A. Hoy and J. J. McKelvey (eds.). Genetics in relation to insect management. Rockefeller Foundation, U.S.A., pp. 97-105.
31. Rudd, R. L. 1964. Pesticides and the Living Landscape. The University of Wisconsin Press, Madison, Wisconsin. 320 pp.
32. Sailer, R. I. 1976. Organizational responsibility for biological research and development inputs. In Organized programs to utilize natural enemies of pests in Canada, Mexico, United States. Animal and Plant Health Inspection Service, USDA, No. 81-28, 10-18.
33. Stern, V. M., R. F. Smith, F. van den Bosch, and K. F. Hagen. 1959. The integrated control concept. Hilgardia 29:81-101.
34. Strong, D. R., J. H. Lawton, and R. Southwood. 1984. Insects on Plants. Blackwell, Oxford. 313 pp.
35. van Lenteren, J. C. 1986a. Evaluation, mass production, quality control and release of entomophagous insects. In J. M. Franz (ed.). Biological Plant and Health Protection. Fischer, Stuttgart, pp. 31-56.
36. van Lenteren, J. C. 1986b. Parasitoids in the greenhouse: Successes with seasonal inoculative release systems. In J. K. Waage and D. J. Greathead (eds.). Insect Parasitoids. Academic Press, London, pp. 341-374.
37. van Lenteren, J. C. 1987. Environmental manipulation advantageous to natural enemies of pests. In V. Delucchi (ed.). IPM Qou Vadis. Geneva, Parasitis Symposium Book, pp. 123-163.
38. van Lenteren, J. C. and J. Woets. 1988. Biological and integrated control in greenhouses. Ann. Rev. Entomol. 33:239-269.
39. Vereijken, P. 1986. From conventional to integrated agriculture. Netherlands Journal of Agricultural Science 34:387-393.
40. Vereijken, P., C. Edwards, A. El Titi, A. Fougeroux, and M. Way. 1986. Proc. Workshop on Integrated Farming. Bulletin IOBC/W.P.R.S. 1986/IX/2. 34 pp.
41. Voronin, K. E. 1982. Biocenotic aspects of Trichogramma utilization in integrated plant protection control. In Les Trichogrammes, le Symposium International. Les Colloques de l'INRA 9:269-274.
42. Way, M. J. 1973. Objectives, methods and scope of integrated control. In W. P. Geier, L. R. Clark, D. J. Anderson, and H. A. Nix (eds.). Insects: Studies in Population Management. Ecological Society of Australia Memoirs 1:1-17.
43. Wilson, T. F. 1985. Estimating the abundance and impact of arthropod natural enemies in IPM systems. In M. A. Hoy and D. C. Herzog (eds.). Biological Control in Agricultural IPM Systems. Academic Press, New York, New York, pp. 303-322.
44. Zadoks, J. C. 1984. Epipre, a computer-based scheme for pest and disease control in wheat. In E. J. Gallagher (ed.). Cereal Production. Butterworths, London, pp. 237-244.

British survey shows 51 percent of consumers interested in organic foods

A recent consumer survey of 1,831 people in England and Wales showed that 28 percent were "definitely interested" in organic food, while a further 23 percent were "possibly interested," reports Christopher Stopes of the Elm Farm Research Center in England. More than three-quarters of people surveyed said they would buy organic foods "if they were more freely available." And 65 percent of respondents felt that residues of agrichemicals were increasingly appearing in food. The results are part of a major survey of public attitudes toward farming conducted in March, 1988, by Research Surveys of Great Britain.

In 1987 British organic producers were not meeting the market demand for these products, and as much as 60 percent of the British demand for organic produce was being filled by imports, Stopes reported. The survey is summarized in the Summer, 1988, issue of *New Farmer and Grower*, a quarterly publication of the British Organic Farmers and the Organic Growers Association, 6 Colston Street, Bristol BS1 5BB.

Low-input, organic certification bill offered in Senate

In a move aimed at spurring discussion before the 1989 Congress opens, Georgia Senator Wyche Fowler has introduced a comprehensive bill to promote low-input agriculture. The bill also has strong land and water conservation sections and proposes a national certification program for organically grown foods. Provisions of the bill include:

- low-interest loans, crop insurance premium reductions, and base acreage protection as incentives for farm transitions to low-input methods;
- on-farm low-input demonstration programs involving 2 million farm acres in 1990 and 10 million in 1991; farmers involved would implement five-year low-input transition plans developed with the aid of USDA;
- a wetland restoration program aimed at putting previously drained farm wetlands under permanent conservation easements;
- expansion of the 1985 Conservation Reserve Program from 45 to 70 million acres, to include substantial portions of land in trees;
- limits on access to federal farm programs by farmers whose land contains wells or surface water contaminated by pesticides;
- the establishment of a national voluntary certification and labeling program for farm commodities produced with organic practices.

The Farm Conservation and Water Protection Act of 1988 (S. 2898) should accelerate the transition of American agriculture "from heavy dependence on chemical inputs to safer, healthier, and more environmentally sound farming methods," Senator Fowler said. Information on the bill is available from his office at 204 Russell Senate Office Building, Washington, DC 20510.

Economics of biological control of pests

Gerald A. Carlson

Abstract. *Biological pest control techniques usually have identifiable costs and constraints that they must overcome before they will be adopted by farmers. Many biological control agents are developed in the public sector and need economic assessments at an early stage. The methods often have hidden costs related to farm labor adjustments or initial costs of development. Living biological controls frequently escape, and they may be disrupted by pesticides, regulations, or farm commodity programs. Pest control registration procedures and small markets also present obstacles. Area-wide implementation programs and changes in incentives for researchers may speed development and adoption of biological controls.*

Key words: costs, constraints, farm labor, startup costs, pesticides, vegetables, small markets

Introduction

Despite the efforts of crop protection researchers over the past four decades, use of biological controls against agricultural pests is limited relative to chemical and other methods (see biocontrol sections in Frisbie and Adkisson, 1985). Certain types of crops, such as orchards and greenhouse vegetables, are much more amenable to biological control of insects, both in the United States and elsewhere (Clausen, 1978; Bal and Van Lenteren, 1987). Control of one organism by another is less common in cereals, cotton and other extensively grown crops. A primary question from the viewpoint of economic feasibility is why some crops and pests are more suited to biological control than others.

In this paper, the term "biological control" is used in a broad sense, following the work of Cook and others (Cook, 1988). It includes single or repeated introductions of living organisms, various cultural practices to enhance natural enemies, and microbial pesticides to suppress weeds, plant diseases and arthropod pests. Some introductions of insect and weed predators have been highly successful, yielding high benefits with low costs. But once the easiest introductions have been made, further progress requires more extensive biological research and implementation efforts.

Biological control is often deemed superior to chemical pest control because of the latter's higher social or external costs, especially hazards to the health of others and damage to the environment. However, these costs are not necessarily considered explicitly by farmers when they choose between chemical and biological pest control methods. Rather, the main considerations in adoption decisions by private users are the costs and returns that they experience themselves. The farmer remains the judge of the suitability of biological control techniques.

As an indication of the economics of the system that biological control must compete with, Figure 1 shows aggregate expenditures per crop acre (adjusted to 1967 dollars) for herbicides, insecticides, and fungicides (derived from unpublished USDA data [Miranowski, 1986]). There are two points to glean from this aggregate view of pesticide use history in the United States. First, as is well recognized, there has been a rapid rise in herbicide use, a slight increase in insecticide use, and an almost constant level of fungicide use. The second point, which is not so widely appreciated, is that pesticides are not very expensive per acre of cropland grown. It is difficult for other pest control methods to compete with these low-cost methods. ("Cost" as used hereafter refers to the private cost paid by farmers.) Of course, some cropland receives no pesticide treatment (partly because of biological control), so average cost per treated area is higher than the figures shown here, particularly for insecticides and fungicides. In fact, pesticide costs for some farmers come to as much as 20 to 30 percent of total variable costs. Not shown in this graph is the recent decline in pesticide prices, amounting to about 15 percent in the past four years. Compared to the prices of other farm inputs such as land, labor, machinery, and fertilizers, pesticide prices have been falling in U.S. agriculture for the past several decades (USDA, 1967-1988). Therefore, developers of biocontrols have a difficult task in coming up with economically competitive alternatives.

As researchers develop new biological control systems, it is wise for them to consider the full range of costs these systems impose on farmers and on suppliers of the necessary materials. Are there expensive adjustments in the farming system that must be made to use the biological controls? There may be costs that are hard to measure in small-scale experiments or in prototypes systems. The costs of biological control as used by the farmer must be compared to those of existing and potential chemical systems.

Finally, there may be institutional and organizational obstacles to biological control. Farm commodity programs may influence the mix of crops and the effectiveness of cultural pest controls. Organizations may have to be established that can implement area-wide bi-

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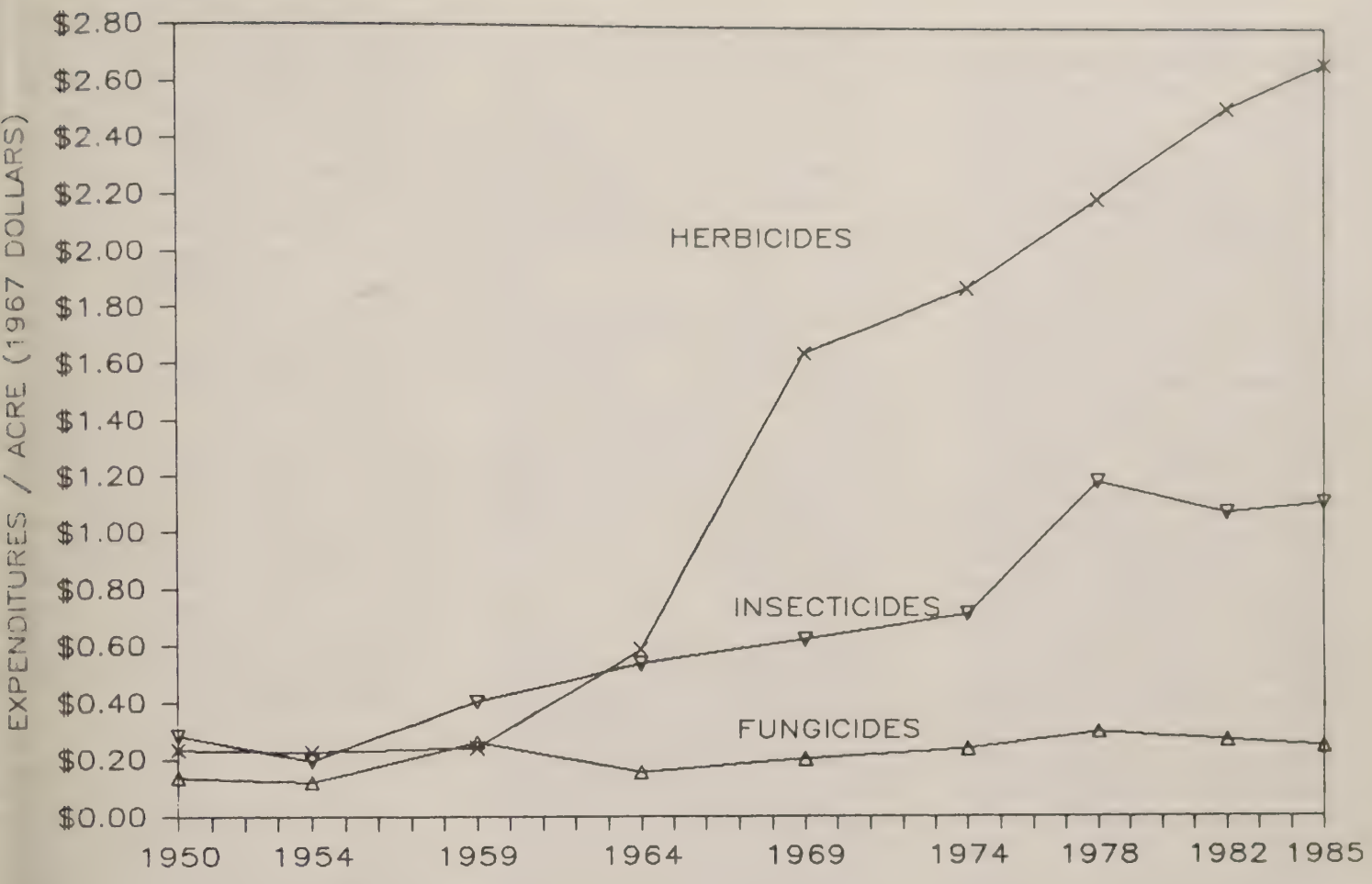

Figure 1. U.S. pesticide expenditures per acre of cropland harvested (unpublished U.S. Department of Agriculture data, Miranowski, 1986; Agricultural Statistics, 1985).

ological control programs. Existing area-wide pest control programs can offer guidelines for expansion of biological control efforts. Each of these possibilities is examined below.

Economic feasibility of biological control at the farm level

Both economic and biological factors influence a farmer's desire to adopt biological control methods. Reichelderfer (1981, 1984) has discussed the relationship of many of these factors to the economic feasibility of controlling both insect pests and weeds. Economic feasibility refers to the "capability of a given biological control technique to yield equivalent or greater net returns to its user as do current [pest] control practices" (Reichelderfer, 1984). She argues that assessment of economic feasibility at the farm level is a necessary first step because if techniques are not feasible for the target user group they will not be used without subsidies. Analysis of all social costs is difficult; we can skip it for those biological control techniques that clearly are not acceptable to farmers.

Some of the major biological and economic factors influencing the economic feasibility of biological control methods are shown in Table 1. Severity of pest damage refers to crop loss from weeds, insects, or plant diseases for common infestation levels. In general, the most voracious insects or most competitive weeds are controlled by pesticides, whereas minor pests or key pests with slow growth are more susceptible to biological methods. Since many biological agents are highly specific to particular species, the simultaneous presence of several damaging species in a field will lower the overall effectiveness of biological techniques relative to a broad-spectrum pesticide. Similarly, pest populations that vary sharply over time

Table 1. Relationships between biological and economic factors and economic feasibility of biological control (after Reichelderfer, 1981).

Factors	Effect on Economic Feasibility
Biological	
severity of pest damage	decrease
pest spectrum in the field	decrease
pest population variability	decrease
technical efficacy of B.C. agent	increase
Economic:	
crop price and yield	increase
costs of non-biological methods	increase
all costs of biological control	decrease
net benefit of B.C. agents versus alternatives	increase

and space may lower the season-long effectiveness of living biological control agents. Even passive biological approaches such as resistant crop cultivars may be less acceptable to farmers than pesticides, since they often have lower yields than susceptible cultivars when major pests are not present (Carlson and Main, 1976). High and variable pest populations that can be easily monitored are commonly managed with some use of pesticides. Obviously, the technical effectiveness of the biological control agent increases the possible economic gains relative to other approaches.

Economic components in Table 1 refer to crop yields and crop production costs for biological versus other means of pest control. Crops that have high value per unit area (high yield, high price) are more likely to be suited to classical biological control systems. Most success stories for orchard, greenhouse and vegetable crops fit this pattern. This may be because of the higher costs of developing a control that fits the widely varying environmental conditions of field crop production. But it also reflects the fact that the costs of conventional methods (mechanical, chemical) are generally lower for field crops than for fruits and vegetables. Some successful biological agents have recently been introduced where pesticide resistance or other factors have raised the cost of existing chemical methods. All costs of biological controls need to be considered. Even disruptions in facilities for rearing biological agents must be covered by farmers or by public expenditures.

Economists and farm management specialists often prepare partial budgets to help farmers compare pest control and other technologies (Reichelderfer et al., 1984; Perrin et al., 1976). Table 2 gives a few items of a hypothetical budget for three pest control approaches to achieve the same crop output. A "+" represents intermediate cost conditions; "−" is a cost reduction and "++" represents a cost increase. Actual budgets would have numerical values based on estimated costs from farmer surveys and on-farm tests, but this exercise can help us compare relative costs. Purchased inputs require immediate cash outlays. Pesticide purchases will usually be highest for the conventional pesticide use, lowest for biological control, and intermediate for integrated pest management (IPM). Other direct expenditures may be higher for biological control than for conventional or IPM aproaches. This is especially true if more land must be cultivated to achieve the same total production because the biological agent suppresses pests less effectively than pesticides. A particularly attractive feature of using chemical pest controls is the saving in labor costs. In most cases, IPM systems and biological control require more precise timing and adjustments of fairly complex factors than does application of pesticides. Systemic pesticides, seed treatments, and routine herbicide applications are easy to use against commonly ocurring pests. Pest control labor for application and pest monitoring are also higher for some IPM and biological control techniques. Although pesticides have their disadvantages, realistically speaking they are attractive to farmers because they often release labor and management for other activities. The final labor cost category is "other labor," which is unrelated to direct pest control. This refers to costs of the cultural control aspects of many biological control systems, and is illustrated further under "hidden costs" in the next section.

The final feature shown in the budgets of Table 2 is the certainty of obtaining the expected yield. The budgets are designed to show costs to achieve equal intermediate crop yield and gross return. However, farmers, like most business people, are averse to income variability (Anderson et al., 1977). They will sacrifice income by buying insurance and using risk reducing inputs such as irrigation or extra equipment. Economic studies of pesticide-intensive systems generally have found that they reduce income variability (Cochran and Boggess, 1988; Carlson, 1984). In some applications of biological control, such as when the agent is slow acting or there is an unusual pest infestation, yields can be highly variable (Reichelderfer, 1981). Biocontrol agents frequently are more susceptible to variation in abiotic and environmental conditions than are most pesticides. Hence a principal consideration in farm level comparisons is the higher yield variability of some biological control techniques.

Table 2. Farm level comparison of costs and returns by category for three pest control approaches*

	Conventional Pest Control	IPM	Biological Control
Purchased Inputs:			
pesticides	++	+	−
cultural or biocontrol agents	+	+	++
Labor Costs:			
Management time	+	++	++
Pest control labor	−	+	+
Other labor	+	+	++
Returns:			
Yield	+	+	+
Yield certainty	++	+	−

* + refers to intermediate costs or return, — is a reduction and ++ represents an increase relative to the intermediate level.

Hidden costs

The long-term adverse effects of pesticides on farm level profitability were discussed in much of the early pest management literature (Smith, 1970). Pesticide resistance and damage to natural enemies of pests are among the major biological sources of extra costs to neighboring farmers. There also are effects on consumers from pesticide residues. Consumers and food processors must constantly make tradeoffs between some desirable food characteristics achieved with pesticide use (fewer insect parts and less damaged produce) versus lower pesticide residues when fewer pesticides are used.

Similarly, biological control approaches may also have indirect or hidden costs. Researchers need to know these costs to overcome them in their development efforts. Like the partial budgets of Table 2, detailed budgets can be developed for individual components of biological control systems. Table 3 lists several cultural practices that are often used to enhance beneficial species, and the development costs of biocontrol agents. The pest suppression benefits from changes in row spacing, planting time, or crop rotation do not result only

Table 3. Hidden costs of biological control tactics and biocontrol development

Biological Control Tactics and Development	Extra Costs
Tactics:	
change in row spacing	—equipment purchases or modification —labor to adjust equipment
planting time adjustments	—more planting labor or equipment —sacrificed yield in other crops —sacrificed income in another job —higher labor costs —lower crop prices
crop rotation	—must also grow lower value crop —delayed income —more management time —negative carry over effects
Development:	
production costs	—biocontrol agent unavailability —higher production costs with low levels of adoption
regulation	—registration and tolerances —liability suits

from enhancing the effectiveness of beneficial species; weather and habitat effects may also contribute. Since these practices may also be part of conventional pesticide or IPM systems, the extra costs of these practices should be partially attributed to pesticide and IPM approaches. These cultural activities are sometimes thought to be "costless," so that farmers could be expected to make them if they only knew that they would help suppress pest populations and reduce crop damage. However, experimental data, farmer records, and studies that include the costs of acquiring information show that there are few cases where farming adjustments are truly costless.

Changes in row spacing are often suggested as a way to enhance predator populations, increase diseases of insect pests, or reduce weed competition. Farmers have gradually reduced row spacing for some major crops like soybeans, but there are costs of making these changes: equipment purchases, extra labor for equipment adjustment, and even yield reduction in the absence of major pests.

Adjustments in planting time as part of a program to enhance natural enemies can also be inconvenient for farmers (Reichelderfer et al., 1984; Moffitt et al., 1984). To plant at a time when weather conditions are less suitable will require more labor or equipment and may reduce yield. Planting later might mean disruption of crucial activities on another crop or another job. These disruptions in turn raise the actual cost per unit of labor. Finally, some farmers may be producing for higher price periods or higher quality markets. Changing planting schedules could cause quality to decline because of less than optimum weather, or could lower the price received for crops because they are not available when the market is at its peak.

Crop rotation is an important biological control practice, although it may also be used to supply nutrients and to improve the soil in other ways. Its primary short-term cost is the lower return from the lower-valued crop in the rotation. Also, the non-susceptible crop, which might generate lower profits, often must be grown first. This delays planting of a higher value crop. Rotations can be complex, especially if farm commodity programs, soil fertility, and availability of equipment restrict the cropping patterns that can be followed. Complex rotations require considerable farm management skills and information. Land grant colleges can assist farmers by determining optimal rotations for various pest problems (Zacharias et al., 1986). Delayed income, management time, and positive and negative chemical carry-over effects must be included in such studies. Unforeseen changes in farm programs, pesticide cancellations, and changes in crop prices require rotation systems to be flexible.

Unavailability of high-quality biocontrol agents can also be a hidden cost of biological control programs. There may be only one laboratory rearing a predator or producing a microbial pesticide. Rearing facilities for sterile insects have been disrupted by contamination and labor strikes (Chambers and Ashley, 1984).

Producing biocontrol agents usually entails start-up costs and economies of scale. Widespread adoption of the biocontrol agent will lower the cost to the farmer. However, uncertainty about the level of adoption remains a problem, especially for minor crops or for pests that only infest small areas. Also, after considerable development expenses have been incurred, a biocontrol agent might be judged too harmful to non-target pests or crops. This type of conflict occurred for release of a biocontrol for a weed in Australia (Paterson's curse) (Auld et al., 1987). In addition, microbial pesticides must go through the federal pesticide registration process; this imposes a higher cost per acre the smaller the area of the target pest and crop. Among the major ways of subsidizing biocontrol agents and minor use pesticides are state research efforts such as the Inter-Regional IV program (IR-IV) to obtain food tolerances and registrations. Since more safety tests (ground water, toxicological, food and environmental residue) are being required for registration, these development costs will increase for microbial pesticides. Finally, developers of all pest controls are vulnerable to product liability suits, an especially serious problem if the costs cannot be spread over a large market. The costs of developing and marketing microbial pesticides will be passed on to farmers or other users unless these activities are publicly supported; however, public funds for such purposes are limited.

This description of hidden costs does not mean that biocontrol agents necessarily are more expensive for farmers than other pest control approaches. However, since much of the biocontrol development has been conducted by public research efforts, evaluations of costs and returns have not been as thor-

ough as they have been for private businesses. Recent Federal legislation that allows public employees to share in the proceeds from commercialized products is likely to induce researchers to make more careful forecasts of market shares and of the relative effectiveness of potential biocontrol products. These public-private cooperative efforts and the increasing costs of product registration should be evaluated economically as we gain more experience and as more products are developed.

Institutional obstacles to biological control

Just as registration is a major obstacle in producing new pesticides, so too there are institutional obstacles in implementing effective biological control. Arrangements affecting more than one farm, or even an entire area, include: methods to insure that farmers who benefit from biological control pay for it; mechanisms that prevent pesticides from disrupting biological control; and changes in farm commodity programs that influence biological pest control.

Three routes by which farm commodity programs might influence biological pest control are listed in Table 4. Farm programs are primarily designed to support farm income, with minimal attention given to other goals. The effects of commodity programs on biological control are less than they might have been because no biological controls are currently used on many program crops. However, program crop acreage can influence the amount of land devoted to commodities for which biocontrol is more common. Program features such as commodity price supports and acreage limitations may influence production methods, and therefore affect biological control programs. For example, higher price supports can lead to increased use of fertilizers, pesticides, and other purchased inputs (Lichtenberg and Zilberman, 1986). The increased use of fertilizers can make crops more attractive to some pests. Greater use of pesticides has frequently been assumed to be an effect of farm programs, although the relationship has not been established. Greater pesticide use may lead to disruptions of predators and less effective biological control on both farm program crops and other nearby crops. Similarly, the acreage restrictions to qualify for price supports may cause shifts in the amount of land planted to program and other crops. Again, the magnitude of such shifts is not well known (Lee and Helmberger, 1985). However, whenever crop mixes shift for farm policy reasons, it is likely that farmers will not use crop rotations that maximize pest control. Finally, the Conservation Reserve Program (CRP) of the 1985 Farm Act provides for removal of between 40 and 45 million acres of marginal land from cultivation by means of ten-year contracts between owners and the Federal government. Retirement of marginal land, most of which so far has occurred in the Plains States, will provide more habitat for both beneficial and harmful organisms.

Table 4. Possible effects of commodity programs on biological control.

Farm Program Feature	Agricultural Input Changes	Biological Control Effect
commodity price supports	more pesticides and fertilizers; changes in planted area	disruptions of predators
acreage requirements	shift in cropping practices	less use of crop rotation
Conservation Reserve Program	less use of marginal land	more beneficials

A second institutional problem involves the adverse effects of legally used pesticides on biological pest control agents. This is a classical "externality" across farms (Reichelderfer et al., 1984). Because biocontrol agents used by one farmer may be suppressed by broad-spectrum pesticides used by another, the latter's pest control choices impose costs that may not be taken into account. Corrective measures may be appropriate, such as changes in the pesticides used or areas of separation in which the use of the two kinds of controls is arranged by agreement, zoning, or regulations. However, these changes would impose real costs for negotiation, monitoring, and enforcement. Because of these costs, and because pesticide use has benefits, in general the economically optimal solution will not be to stop all damage to biological control organisms. Comparisons should be made of the benefits of additional pesticide use (higher yields, lower consumer prices) relative to the additional costs (value of the biocontrol agents disrupted). It is encouraging that in some areas where biocontrol agents are coming into common use, pesticide manufacturers will screen new and older products for possible harm to these agents. When farmers combine biocontrol and pesticides on the same farm, they will attempt to select pesticides that do not disrupt the biological control organisms.

The allocation of research funds between biological and conventional pest control methods should be based on the net benefits of the research. In computing net benefits, the external as well as private costs of pesticides and biocontrol agents must be taken into account. External costs will need to be lower for biocontrol methods to compensate for their higher private costs and lower private benefits. External costs can only be estimated, since they involve values that are difficult to assess (human health, wildlife, aesthetics). Information on the external costs of pesticide use is beginning to be compiled, but so far few quantitative values are available (Yardas et al., 1982; National Research Council 1987).

Methods other than publicly supported research can also promote biological approaches to pest control. Information on using biocontrol technology can lower farmers' management costs and encourage adoption. This was the approach used to foster adoption of IPM programs through the extension service.

An externality problem associated with biocontrol of pests is the escape of biocontrol agents from the farms of those paying for and releasing the agent (Reichelderfer et al., 1984). Nearby farmers with similar crops and pests are free-riders (non-payers) unless they compensate those who have paid for biological control. One reason biocontrol

has been successful in greenhouses, rice fields, and orchards is that such escapes can be eliminated or sharply reduced compared with other crop systems. This type of external effect is an external benefit, except for the rare cases in which biocontrol agents damage other crops or beneficial species.

Groups of farmers can be organized in pest control districts or other area-wide efforts. This can be an important way to reduce escape of biological control agents. Pest control districts have been formed for cultural practices (uniform stalk destruction, early crop termination), pesticide-intensive methods (eradication, diapause), biological control (cooperatives in citrus production), or IPM (area-wide pest monitoring) (Moffitt et al., 1984; Carlson and Suguiyama, 1985).

Some characteristics of an important area-wide eradication program are shown in Table 5. These features may be helpful in forming other area-wide programs to help reduce the costs of pest control through economies of scale, coordination, and reduced escape of both pests and biocontrol agents. Major issues are the optimum size of the area, how costs are to be shared, and how differences in benefits among farmers are to be reconciled.

For the boll weevil program in North and South Carolina, state legislation required regional votes, with a two-thirds majority of all voting cotton farmers needed for approval (Carlson and Suguiyama, 1985). Once the program was approved for an area, it was mandatory, although farmers had the option of not growing cotton, of course. Since operating fees were assessed on a per acre basis, some farmers chose to reduce cotton planting, which in turn reduced the habitat for the pest. The program was established by state legislation, with enforcement handled by state agricultural regulatory bodies. Operating costs were shared by individual cotton farmers (70 percent) and the Federal government (30 percent). State and Federal groups contributed to development and extension activities. To accommodate individual differences in farmer benefits, there were opportunities for program payment rebates for early stalk destruction, and farmers in fringe areas could be paid to divert land to alternative crops. Pheromone traps, computer records, and coordinated suppression with insecticides were major features of the two and one-half year eradication program. Monitoring and costs of cleaning up reinfestations have been minimal in North Carolina in the seven years since eradication was achieved. Overall benefits to North and South Carolina farmers, beginning in the second year of the program, have been a 40 to 70 percent reduction in pesticide expenditures on cotton, a 10 to 15 percent yield increase, and an increase in area planted to cotton even with programs favoring acreage reductions. Environmentally, there is reduced damage to off-farm organisms because of the reduction in pesticide use (Carlson and Suguiyama, 1985). Similar area-wide suppression programs for the boll weevil are under way in Georgia, Florida, and parts of Alabama, Arizona, and California.

Table 5. Characteristics of area-wide boll weevil management in North and South Carolina, 1978-1987 (after Carlson and Suguiyama, 1985).

General Characteristics	Special Features for Boll Weevil Case
legislative approval	two-thirds majority vote of all cotton farmers by state or region
farmer participation	mandatory; farmers can adjust by changing area planted to cotton
cost sharing	70 percent from farmer fees, 30 percent federal
innovative cost features	rebates for early stalk destruction; buy-out options for fringe areas
duration	suppression phase is 2.5 years, monitoring and clean up thereafter
economic results	10 to 15 percent yield gain; 40 to 70 percent reduction in pesticide costs; increased cotton area
environmental results	40 to 70 percent reduction in pesticide use lowers off-farm damages

Summary

Biological control techniques have identifiable costs and constraints that must be overcome before farmers will adopt them. Methods that make intensive use of pesticides are easier than control with living predators and parasites. Biological control systems, including cultural controls, need economic evaluation at an early stage of development. Because most biological control techniques are developed in the public sector, they frequently do not receive the business scrutiny given to pesticides and other commercial products. Biological control organisms often escape, and may be adversely affected by pesticides, weather and, in some cases, Federal commodity programs. Given this unstable environment, it would be wise to subject promising biocontrol techniques to economic evaluation. The public wants safe pest control, but like most services and products this comes at a cost. The public will support only those biological systems that are effective and inexpensive, and that will replace the most harmful pesticides.

References

1. Agricultural Statistics. 1985. U.S. Department of Agriculture, Washington, DC.
2. Anderson, J. R., J. L. Dillon, and J. B. Hardacker. 1977. Agricultural Decision Analysis. Iowa State University Press, Ames, Iowa.
3. Auld, B. A., K. M. Menz, and C. A. Tisdell. 1987. Weed Control Economics. Academic Press, London.
4. Bal, A., and J. C. van Lenteren. 1987. Integrated pest management in the Netherlands: practice, policy and opportunities for the future. Med. Fac. Landbouww. Rijksuniv. Gent. 52(2):385-393.
5. Carlson, G. A., and C. E. Main. 1976. Economics of disease-loss management. Annual Review of Phytopathology 14:381-403.
6. Carlson, G. A. 1984. Risk reducing inputs related to agricultural pests. In Risk Analysis of Agricultural Production Firms: Concepts, Information Requirements and Policy Issues. Proceedings of Southern Regional Research Project S-180. Univ. of Illinois, Urbana, Illinois. pp. 164-175.
7. Carlson, G. A., and L. Suguiyama. 1985. Economic evaluation of area-wide cotton insect management: boll weevils in the Southeastern United States. Bulletin 473. North Carolina Agricultural Research Service, North Carolina State University, Raleigh, North Carolina.
8. Chambers, D. L., and T. R. Ashley. 1984. Putting the control in quality control in insect rearing. In E. G. King and N. C. Leppla (eds.). Advances and Challenges in Insect Rearing. USDA-ARS, New Orleans, Louisiana. pp. 256-260.

9. Clausen, C. P. 1978. Introduced parasites and predators of arthropod pests and weeds: a world review. USDA-ARS, Washington, DC.
10. Cochran, M. J., and W. G. Boggess. 1988. Integrated pest management: risk implication for natural resources use. In Incorporation of Risk in Analysis of Farm Management Decisions Affecting Natural Resource Use. Special Report 821. Agricultural Experiment Station, Orgeon State Univ., Corvallis, Oregon. pp. 15-40.
11. Cook, J. R. 1988. Biological control and holistic plant-health care in agriculture. American Journal of Alternative Agriculture, pp. 51-62.
12. Frisbie, R. H., and P. L. Adkisson. 1985. CIPM: Integrated Pest Management on Major Agricultural Systems. Texas A & M University, College Station, Texas.
13. Lee, D. R., and P. G. Helmberger. 1985. Estimating supply response in the presence of farm programs. American Journal of Agricultural Economics 67(2):193-203.
14. Lichtenberg, E., and D. Zilberman. 1986. The welfare economics of regulation in revenue-supported industries: the case of price supports in U.S. Agriculture. American Economic Review 76(5):1135-1141.
15. Miranowski, J. 1986. Private communication, May. USDA Economic Research Service.
16. Moffitt, L. J., T. Burrows, J. L. Baritelle, and V. Sevacherian. 1984. Risk evaluation of early termination for pest control in cotton. Western Journal of Agricultural Economics 9:145-151.
17. National Research Council. 1987. Regulating Pesticides in Food: the Delaney Paradox. Committee on Scientific and Regulatory Issues Underlying Pesticide Use Patterns and Agricultural Innovation. National Academy Press, Washington, DC.
18. Perrin, R. K., D. L. Winkelmann, E. R. Moscardi, and J. R. Anderson. 1976. From agronomic data to farmer recommendations: an economic training manual. Information Bulletin of the International Maize and Wheat Improvement Center, Mexico City, Mexico.
19. Reichelderfer, K. H. 1981. Economic feasibility of biological control of crop pests. In G. Papavizas (ed.). Biological Control in Crop Protection. BARC Symposium No. 5. Allanheld, Osmun, Totowa, New Jersey. pp. 403-417.
20. Reichelderfer, K. H. 1984. Factors affecting the economic feasibility of the biological control of weeds. In E. S. Delfosse (ed.). Proceedings VI International Symposium of Biological Control of Weeds. Vancouver, Canada. pp. 135-144.
21. Reichelderfer, K. H., G. A. Carlson, and G. A. Norton. 1984. Economic guidelines for crop pest control. FAO Plant Production and Protection Paper No. 58. Food and Agriculture Organization, Rome, Italy.
22. Smith, R. F. 1970. Pesticides: their use and limitations in pest management. In R. L. Rabb and F. E. Guthrie (eds.). Concepts of Pest Management. North Carolina State University, Raleigh, North Carolina. pp. 103-118.
23. U.S. Department of Agriculture. 1967-1988. Economic Indicators of the Farm Sector: Production and Efficiency Statistics. Economic Research Service, Washington, DC.
24. Yardas, D., A. J. Krupnick, H. M. Peskin, and W. Harrington. 1982. Directory of Environmental Asset Data Bases and Valuation Studies. Resources for the Future, Washington, DC.
25. Young, D. L., and W. A. Goldstein. 198?. How government farm programs discourage sustainable cropping systems: U.S. case study. In Proceedings of Farming Systems Research Symposium. Univ. of Arkansas, Fayetteville, Arkansas.
26. Zacharias, T. P., J. S. Liebman, and G. R. Noel. 1986. Management strategies for controlling soybean cyst nematode: an application of stochastic dynamic programming. North Central Journal of Agricultural Economics 8:175-188.

De-bugging the beans in Maine

The expansion of dry bean production in Maine is threatened by the Mexican bean beetle now spreading in the state, reports a University of Maine article. So scientists Matt Liebman and Randy Alford are studying the responses of the beetle to alternative crop management practices in the hope of overcoming that threat.

Strip cropping of beans and corn, intercropping, and manipulation of weeds have helped in some other states, the Maine scientists say. The beetles fly in, trying to locate their host plant, and anything that keeps them from recognizing their host works in favor of the crop. Tall corn plants or some weeds can affect the ability of the insect to locate the bean plant.

The research is reported along with other low-input work in progress in Maine in the September issue of *Research for Maine and Its People*, the newsletter of the Agricultural Experiment Station (Vol. 1, No. 8). For information, contact the Maine Agricultural Experiment Station, University of Maine, Room 1, Winslow Hall, Orono, ME 04469-0163.

Fifty-year easements for farm debt relief

Financially stressed farmers with Farmers Home Administration loans dating back to 1985 can gain some debt relief by exchanging a conservation easement for a portion of the debt, according to new USDA regulations announced in mid-October. Debt relief is provided in exchange for at least a 50-year conservation easement. The amount of relief is based on the cash flow needs of the borrower.

Easements can be established for conservation, recreation, and wildlife purposes on farm property that is wetland, upland, highly erodible land, or wildlife habitat. An easement review team will be led by the Soil Conservation Service, with the Fish and Wildlife Service participating when wetlands are involved.

The conservation easement option was authorized in the 1985 farm bill. Farmers Home Administration officials estimate that they have about 242,000 borrowers, of which 118,000 are in some form of default. About 65,000 of those borrowers will still have a negative cash flow after all other forms of debt restructuring except easements are considered, FmHA estimates.

Biological pest control: Needs and opportunities

Waldemar Klassen

Abstract. *The extent to which pests should be managed by biological versus chemical methods has been a burning public policy issue since about 1950. A thorough policy analysis is needed to facilitate movement beyond the status quo. Such analysis should: a) review the extent of adoption of ecologically selective methods of pest control that have emerged from the last three decades of research, b) examine changes in policies, legislation and institutional arrangements that would foster more rapid and widespread adoption of environmentally benign pest controls, c) assess the role of biological controls in facilitating survival of farms during periods of economic adversity and in increasing the competitiveness of American agriculture, d) evaluate opportunities to use ecologically selective pest controls to improve water quality, to reduce environmental impacts of pests and of farming practices, and to preserve the usefulness of pest-resistant crop cultivars and pesticides, and e) identify options and mechanisms to further increase the flow of private and public resources into biocontrol research, development and implementation. A committee of highly accomplished and respected citizens needs to be formed to conduct a thorough analysis of the above and other issues related to the long-term economic viability of farming and to the development and widespread adoption of agricultural practices that will conserve and improve the resource base, and that are devoid of negative impacts on the environment and public health.*

Key words: Rachel Carson, *Silent Spring*, 1962, pesticide residues, cranberries, milk, biocontrol, public policy, ground water protection, plant toxins, mutagens, oncogens

The genesis of a public policy issue

The Research Briefing Panel on Biological Control in Managed Ecosystems (Cook et al., 1987) has asserted that "biological control should become the primary method used in the United States to ensure the health and productivity of important plant and animal species." The extent to which pests should be managed by biological versus chemical methods has been a burning public policy issue since about 1950.

During the mid-1950s, and before general ecologists and environmentalists became alarmed over hazards of broad spectrum pesticides, agricultural scientists were already addressing the issue. For example, during the mid-1950s, Dr. E. F. Knipling redirected the program of research on insect control within the Agricultural Research Service from primary emphasis on chemical control to primary emphasis on the discovery and development of nonchemical methods of control (Knipling, 1979). Also during the mid-1950s, Dr. Ray F. Smith and others at the University of California formalized the concept of integrated control in which the beneficial actions of biological agents are supplemented with pesticides (Stern et al., 1959). In 1962, Rachel Carson published *Silent Spring*, a book that warned against the extensive use of chemical pesticides and pleaded for more research on biological methods of pest control (Carson, 1962). Both the Administration and Congress responded to this concern, and substantial additional funds were appropriated to various Federal and State agencies for research, development, and implementation of more ecologically selective, safer, and more socially acceptable methods and systems of managing pest problems.

Subsequently, intense public concern was expressed concerning pesticide residues on cranberries and in milk. Tainted products had to be destroyed, and producers demanded compensation from Congress. Thus, in 1966, Congressman Jamie L. Whitten published a book, *That We May Live*, in which he expressed concern that the general public not lose its appreciation for the value and essentiality of agricultural chemicals to our health and propserity. Clearly a balance had to be struck between conserving the use of established technologies (which possessed some intrinsic disadvantages) and rapidly developing pest controls with fewer negative attributes. The nature of this balance constitutes a major public policy issue.

Need for policy analysis vis-a-vis biological control

Joseph Coates (1979) defines a public policy issue as a fundamental enduring conflict among or between objectives, goals, customs, plans, activities or stakeholders which is not likely to be resolved in favor of any polar position in the conflict. As scientists, we tend to be uncomfortable with issues. We are comfortable with problems because they have solutions. Further, David Rose (1981) has commented that scientists, when faced with the complexities and paradoxes of issues, selectively ignore vital aspects and concentrate on one or a few simple features as if these were the whole. This he calls *selective inattention*. In addition to selective inattention, a mismatch often occurs in the time perspective in which people with different views focus on different times in the future and, thus, make different responses. Through se-

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lective inattention and differences in time perspectives, scientists often break down complex policy issues into small problems that they feel comfortable in tackling (Rawlins, 1984).

In any case, after four decades of debate concerning the degree to which biological pest controls should be used versus chemical control, neither scientists nor policymakers have arrived at a broad consensus. The proposition I want to advance is that a thorough policy analysis is needed as a guide to the Congress and to the Administration.

The policy analysis should address a series of issues including the following:

1. To what extent have the findings from the last three decades of research on biological control and other ecologically selective methods of control been adopted?

2. What changes in policies, legislation and/or institutional arrangements would foster significantly greater adoption of safer and more environmentally benign approaches to managing pest problems?

3. To what extent would greater use of available biological controls enable farmers to survive periods of economic adversity?

4. To what extent would greater use of available biological controls retard the development of resistance in pests to pesticides, and the development of new strains of pests that can overcome genetic resistance to them in crop cultivars?

5. To what extent would modest increases in levels of effort in biocontrol research, development and implementation improve the productivity of rangelands and forests?

6. To what extent would greater use of available biological controls result in improved quality of surface and ground water, reduction in soil erosion, and improved safety of the food supply?

7. To what extent would greater use of biological controls in the protection of horticultural crops reduce the incentive to develop pest-resistant cultivars that contain high levels of natural plant toxins, mutagens, and oncogens? Examples of such substances include psoralens in insect-resistant celery, alkaloids in insect- and disease-resistant tomatoes and potatoes, and indole carbinols in cole crops (Ames, in press).

8. What are the prospects for enhancing the joint use of biocontrol agents and synthetic chemical pesticides?

9. What options and mechanisms can be identified to further increase the flow of private and public resources into biocontrol research, development, and implementation?

There is no shortage of excellent expositions of opportunities and priorities in pest control research and implementation. Recent examples include a conference proceeding edited by Hoy and Herzog (1985) on "Biological Control in Agricultural IPM Systems," the National Academy of Sciences Research Briefing Report on Biological Control in Managed Ecosystems (Cook et al., 1987), and the report of the Research Priority Setting Meeting for the ARS Biological Control Program (ARS, 1987). But, in the absence of a new and explicit policy, these fine assessments of opportunities, priorities, and needs will not receive much attention by private firms and public sector institutions.

The process of policy formation in a democracy is complex, tortuous, and disorderly (Lindblom, 1968). Policy formation is the responsbility of our elected and appointed political leaders. They must consider the trade-offs between the broad public interest and the various regional and special interests. However, I believe that skilled objective analysis of the major issues in the biological/chemical control question will raise the level of the debate, and it is likely to be highly influential and perhaps even decisive.

Among other things, a policy analysis in relation to the biological and chemical control of harmful organisms must examine the advantages and disadvantages of the two approaches relative to one another. The analysis should address short- and long-term benefits and costs of each approach and the array of institutional adjustments that may be needed to move beyond the status quo in improving the ability of farmers to survive hard times, improving environmental quality, sustaining the productivity of soils, and further improving the safety of the food supply (Reichelderfer, 1981, 1985; Ridgway, 1981; Starler and Ridgway, 1977). Further, such analysis should examine some of the factors that appear to be driving toward a greater effort in the development and implementation of biological methods. I will touch briefly on some of these topics.

Strengths and limitations of biological and chemical controls

Let us briefly consider the status and characteristics of biological versus chemical control for the major groups of harmful organisms.

Biological control of cropland weeds is still in its infancy. Almost 70 percent of the volume of pesticides used in the United States consists of herbicides or weed killers (Ayers, 1985; Gianessi, 1987; Kearney, Isensee, and Plimmer, 1988), and most of this volume is used against the complex of weed species on cropland. Usually there are 20 or 30 species of weeds on every hectare of cropland. Therefore, a method which selectively removes only one or a few species has little value because the remaining weedy species will quickly replace those that have been removed. Thus, in most cases, a high degree of selectivity of an agent for the control of a weedy species has little merit for the control of weeds in most cropland situations (Reichelderfer, 1981).

As noted by Day (1978): "There are currently two basic means by which the farmer can achieve essentially weed-free conditions in cropland: tillage and herbicides. These basic methods are supplemented and modified by a variety of preventive, biological, and ancillary managerial practices, but the basic decision is whether to plow or to spray. With modern machinery and selective chemicals each choice can be highly effective and each can be harmful in its own way. In the United States we are currently at the halfway point. Herbicides serve as a supplement to tillage in some instances but in others have replaced tillage. The trend to substitute herbicides for cultivation is in full swing and the end point is by no means clear." (Actually, nationwide the acreage

planted in conservation tillage in 1987 was only 37 percent (USDA, 1988), and thus less than the "halfway point.")

Both tillage and herbicide use can have very substantial drawbacks. Preplant and pre-emergence herbicides leave residues and contaminate ground water. Cultivation leads to the erosion of 20 to 40 tons of topsoil per hectare each year. Cultivation disrupts soil structure and requires tremendous quantities of energy. Cultivation of soil is by far the largest materials moving activity in the world.

During the past four decades, most of the herbicides that came into use had to be applied at one kilogram or more per hectare. However, in recent years new types of herbicides have been discovered that are effective at merely 10 to 20 grams per hectare. Thus, the environmental load of these newer herbicides is very low. Eventually, these new herbicides may displace a substantial portion of the older herbicides.

A decade ago, there seemed little hope that biological control of cropland weeds would ever become a reality. However, as pointed out by Dr. Templeton in this Symposium, plant pathogens are being developed that control certain cropland weeds. Eventually, combinations of mycoherbicides and other biological agents may become available to control the complexes of weed species that are found where major cultivated crops are grown (Quimby and Walker, 1982; Templeton, Smith, and TeBeest, 1986).

Aquatic weeds, unlike cropland weeds, have proven to be excellent candidates for biological control. Usually only one species (e.g., alligator weed, water hyacinth, milfoil, etc.) is present so that the narrow selectivity of many biological agents is not a disadvantage. In addition, the treatment of bodies of water with chemical herbicides is undesirable.

Rangeland weeds in some cases have proven to be excellent candidates for biological control. Often only one major weedy species is involved. Successful examples include klamath weed and tansy ragwort in the Pacific states, lantana rangeweed in Hawaii, musk thistle in eastern and western states, and punctureviné in California and Hawaii (CEQ, 1972).

On the other hand, in some cases people do not agree that a given plant is a weed - for example, mesquite (Andres, 1981; Batra, 1981). In such cases, use of biological agents may be inappropriate because they cannot be restricted to property boundaries. Thus, at this time, control of rangeland vegetation that is valuable to some but detrimental to others may continue to be achieved by mechanical or chemical means.

Within the public sector in the United States, only about 35 scientist years of effort are devoted to discovering and developing biological methods of weed control (Quimby and Boyette, 1987), whereas there are about 480 scientist years of effort devoted to the discovery and development of herbicides (McWhorter et al., 1984).

About 25 percent of the volume of pesticides used in the United States consists of insecticides. During recent decades, the volume of insecticides used has declined steadily, whereas the usage of herbicides has increased. Beginning in about 1970, a consensus developed among American entomologists that most insect problems should be handled by means of integrated pest management systems, such systems are best generated from an extensive knowledge of the biology and ecology of pests, pest populations should be closely monitored, and that, whenever feasible, the pest management system should be built on a foundation of crop resistance. By means of this approach, it has been possible, in many cases, to obtain substantial benefit from indigenous biological control agents, and reserve the use of chemical insecticides as a last line of defense. This strategy has been quite successful against many pests of major field crops such as sorghum, small grains, soybean, and certain pests of corn. However, this strategy has been less successful against cotton pests. Little progress has been made in developing corn hybrids that are resistant to the corn rootworm complex; nevertheless, breeding lines have been developed with very large root systems. These large root systems impart some tolerance to rootworms. Indeed, about one-quarter of all insecticide use in U.S. agriculture is allocated to protecting corn against rootworms (Economic Research Service, 1983). Also, this strategy has not been highly successful against insect pests of high value fruit and vegetable crops. Dr. Hoy, in this Symposium, gave us a good overview of traditional and emerging technologies for coping with insect pests.

About 5 percent of the volume of pesticides used in the United States consists of fungicides. For many decades, the two major approaches to dealing with plant disease problems have been the development of resistant crop cultivars and the reduction of sources of inoculum by cultural measures (Klassen et al., 1975). However, as we heard in this Symposium from Dr. Cook and from Dr. Lumsden, a number of very promising biological control approaches for plant pathogens are now being developed, and some are being commercialized. However, with regard to nematode control, we have a serious crisis. Neither chemical nor biological means exist to deal effectively with many nematode problems.

We now have a fairly good appreciation of the advantages and disadvantages of chemical pesticides and the properties that biological agents must possess if they are to compete with chemical pesticides.

With regard to the disadvantages of heavy reliance on pesticides (especially when used in suboptimal control strategies), we have witnessed (1) the emergence of insect strains decisively resistant to insecticides and of plant pathogens decisively resistant to fungicides and other antibiotics, (2) the depletion of natural control agents and the elevation of minor pests to major pest status, (3) ecological shifts in weed populations whereby weeds susceptible to herbicides are replaced by species more difficult to control, and the development of herbicide-resistance in a fairly small number of weed species, and (4) residues of pesticides in food, drinking water, and elsewhere in the environment.

Chemical controls must be applied on an ongoing repetitive basis, and they rarely provide enduring cures for pest problems. By contrast, enduring or perpetual solutions to pest problems at little or no recurring cost have been provided

in a significant number of cases by "classical" biological control and by crop resistance. Examples include the biological control of many species of alien insects and weeds that became established in the United States and by multigenic resistance to important crop diseases such as wheat rusts.

On the other hand, chemical pesticides have some highly favorable attributes. Most pesticides have the broad action spectrum that is useful in coping with numerous harmful species. Let us not forget that agriculture must be defended from about 8,000 species of fungi, 10,000 species of insects, and 2,000 species of weeds (Klassen et al., 1975). Roughly 10 percent of these harmful species are perennially important. Even if we had biological means available to cope with the worst of the harmful species, chemicals would probably still be needed to deal with the legion of relatively minor harmful species. The vast array of harmful organisms can be controlled by one or more of the many available pesticides.

Generally effective patent protection can be obtained for chemical pesticides. On the other hand, there appear to be difficulties in obtaining adequate patent protection for certain biological methods of control.

Chemical pesticides are readily available throughout the world as is the equipment to apply them. In contrast to some biologicals, chemical pesticides tend to have a long shelf life. They can be manufactured in the off-season and shipped long distances. Chemical pesticides fit well into our private enterprise agriculture. They provide a means whereby the individual farmer or property owner can control pests and pathogens in spite of negligence by neighbors. Because most chemical pesticides have a broad spectrum of action, they have the potential for serving a large market. Also, they can be applied efficiently over large acreages with a minimum of managerial time and attention.

Obviously, the development of biological methods must occur in competition with chemical methods. In some cases, such as the development of resistant cultivars of major crops, this tends not to be a problem. In other cases, substantial input from economists is required. Market niches, market size, the need for modified or new institutional arrangements, etc., are issues that tend to be beyond the training of biological scientists.

During the mid-1970s, the vital role of research economists in developing biological methods and integrated systems was recognized. The Economic Research Service (ERS), USDA, devoted about $1 million per year for this purpose. Several small but excellent teams of economists worked closely with research biologists to help assure the development of efficient, cost-effective pest control systems. Unfortunately, ERS faced higher priorities and was forced to abandon this effort in 1983. However, the need has not diminished and, indeed, has become progressively more urgent.

Short-term versus long-term benefits of biological and chemical controls

There is a need to examine the short-term versus the long-term benefits to the individual user and to society of various mixes of biological and chemical control (Ridgway, 1981). To individual users (e.g., producers) the short-term benefit is the added profit from using the controls minus their costs. Also, the individual user is concerned with reducing risks of losses from potential pest problems. For society, the short-term benefits include lowered costs of food, fiber, housing, beautiful parks and landscape plants, and the protection of human health. The long-term benefits to users include the continuing effectiveness of various methods of pest control--such as the avoidance of development of strains of pests that are resistant to pesticides or that have overcome crop resistance--and favorable public perceptions and attitudes. The long-term benefits for society include reductions in environmental problems and insidious threats to human health caused by certain residues. With regard to pesticide residues, a National Research Council Committee (1982) found "no epidemiological evidence to suggest that these compounds individually make a major contribution to the risk of cancer in humans. However, the possibility that they may act synergistically and may thereby create a greater carcinogenic risk cannot be excluded."

Institutional arrangements need to be examined to provide for protection of natural enemies from pesticide drift or various ways of implementing strategies that are most effective when applied on an organized or community-wide basis.

Outlook for accelerated development and use of biological controls

What is the outlook for an increased effort to accelerate the development of biological methods for controlling harmful species? As everyone knows, there have been no significant increases in funding for such research in the public sector during this decade. However, there have been some modest increases for research on the biotechnologies, and the latter are relevant to the development of biological methods.

Probably the foremost reliable indicator that the development of biological methods is being accelerated is that almost all of the major agrochemical companies, as well as a number of biotechnology companies, have made modest investments in the discovery and development of biopesticides. I estimate that these industrial firms are spending more than $50 million per year on biopesticide R&D. In addition, the various major seed companies, agrochemical companies, and biotechnology companies are estimated to be spending in the order of $200 million per year on plant biotechnology. A significant portion of this investment is believed to be targeted on developing resistant crop cultivars.

Doubtless, several fairly recent developments are causing the private sector to increase investment in research and development on biological methods. One is the enormous cost of discovering and developing new chemical pesticides and in re-registering old ones. Commonly, a commercial firm spends from $25 million to $40 million (Menn and Henrick, 1985) in bringing a new pesticide to mar-

ket. The regulatory requirements under EPA's tier testing guidelines are much less stringent and less costly for biological than for chemical pesticides. Furthermore, genetic engineering and other biotechnologies provide major new opportunities to modify the selectivity, speed of action, persistence, and other properties of biological agents that are needed to enhance their commercial success. Thus, developments in biotechnology have dramatically improved the prospects of tailoring biological methods to the needs of the marketplace.

The increased entry of the private sector into the biological methods arena presents many opportunities for scientists in the public sector to cooperate and make better use of scarce resources. For example, at the Beltsville Agricultural Research Center we are cooperating with Crop Genetics International, a biotech firm at Dorsey, Maryland, in the development of an endophyte, *Clavibacter xyli* subsp. *cynodontis* that has been genetically engineered to produce the *Bacillus thuringiensis* endotoxin to protect the corn plant against the European corn borer. We entered into this agreement with Crop Genetics International because the European corn borer is a serious pest of many commodities, more effective and environmentally compatible controls are needed, we feel that biological control should play a more prominent role in dealing with such difficult pest problems, and because biotechnology, if properly applied, will greatly advance the future use of biological control. In addition, we recognize the importance of improving our ability to work with the regulatory system and improving our ability to communicate with the public on complex issues.

The bulk of the cost, as well as the inconvenience, of obtaining most of the regulatory clearances is being borne by the private firm. We are using the taxpayers' money to ascertain the environmental fate and impact of the genetically engineered organism and the nature of the expression of the *Bacillus thuringiensis* gene in its new environment. In this case, there is no exchange of funds. However, in several other cooperative undertakings at the Beltsville Agricultural Research Center, industrial firms are providing financial resources under the authority of the Technology Transfer Act of 1986.

There are a number of factors that may eventually cause the Federal Government to invest more heavily in the discovery and development of biological methods of controlling harmful organisms. The first of these driving forces is the imperative to improve the quality of ground water. Agricultural chemicals in trace amounts are being found in the water supplies throughout the United States (Agricultural Research Service, 1988a, 1988b; Council for Agricultural Science and Technology, 1985; Nielsen and Lee, 1987; USDA, 1989). Approximately half of the U.S. population obtains its drinking water from underground sources. Also, several states and most rural communities rely on ground water for more than 90 percent of their drinking water. American agriculture has a vested interest in preventing the contamination of surface and ground water by agricultural chemicals. These essential chemicals must be used more wisely and more sparingly. A substantial portion of the use could possibly be offset by substituting biological methods for pesticides. Major increases in Federal appropriations for developing biological methods must be deferred in an effort to reduce the Federal deficit.

A second "driver" is public concern that excessive levels of pesticide residues are present in the food supply. This concern was heightened in 1987 with the publication of the National Academy of Sciences study entitled "Regulating Pesticides in Food: The Delaney Paradox." Also, the passage in California of Proposition 65 is evidence of strong public concern. The latter legislation requires that all foods be labeled that contain traces of oncogens or substances potentially toxic to fetuses.

A third "driver" is the Endangered Species Act. This Act is intended, among other things, to shield rare and endangered species from inadvertent destruction by pesticides. Its implementation on a county-by-county basis will increase the demand for selective biological methods.

Finally, farmers generally are very concerned about staying in business. Lowering the cost of inputs is a matter of survival. Accordingly, Secretary of Agriculture Richard E. Lyng (1988) recently issued a memorandum that asserts the Department of Agriculture's "support for research and education programs and activities concerning 'alternative farming systems'...". Also, in Fiscal Year 1988 Congress appropriated roughy $4 million to the Cooperative State Research Service for a new thrust in low-input agriculture. The balance of international trade in U.S. agricultural products has declined from approximately $24 billion per year at the beginning of this decade to a value of about $7 billion in 1987. Therefore, the competitive position of U.S. agriculture in the global marketplace has become an important national concern.

It seems significant that various members of Congress are concerned about the long-term prospects for U.S. agriculture and for agricultural research. Last October, Congressman George E. Brown, Jr., gave a talk on "Getting to the New Age in Agriculture" (Brown, 1987). He noted that agriculture will not benefit from the tools of biotechnology unless new resources are provided. He noted that USDA funding for agricultural research is still at the 1967 level in constant dollars, while the Federal Government is making plans to spend $6 billion on a super-collider, $4 billion on a space station, and several billion dollars to map the human genome. Congressman Brown recommended an infusion of $100 million for agricultural research.

In conclusion, it appears that there is some movement toward more development of biological controls and toward greater sophistication and better "environmental fit" of chemical controls. Indeed, there are positive signs that the major private firms are shifting some resources toward the development of biological methods. This shift is providing important opportunities for more effective cooperation between the public and private sector R&D capabilities. What seems to be most needed at this time is a policy analysis to help our political leaders examine the need for a new public policy on pest control research and

implementation. I hope that a committee of highly accomplished and highly respected citizens can be formed to undertake this badly needed in-depth analysis.

References

1. Agricultural Research Service. 1987. ARS National Biological Control Program: Minutes of Research Priority Setting Meeting. National Program Staff, Beltsville, Maryland. 154 pp.
2. Agricultural Research Service. 1988a. ARS strategic groundwater plan: 1. Pesticides. ARS, Beltsville, Maryland. 8 pp.
3. Agricultural Research Service. 1988b. ARS strategic groundwater plan: 2. Nitrate. ARS, Beltsville, Maryland. 9 pp.
4. Ames, B. 1989. Environmental pollution and cancer causation: six common errors. In V. T. DeVita, Jr., S. Hellman, and S. A. Rosenberg (eds.). Important Advances in Oncology. J. B. Lippincott, Philadelphia, Pennsylvania (in press). pp. 2-24.
5. Andres, L. A. 1981. Biological Control of Naturalized and Native Plants: Conflicting Interests. pp. 341-349. In G. C. Papavizas (ed.). Biological Control in Crop Production. Allanheld, Osmun & Co. Publishers, Inc., Totowa, New Jersey. 461 pp.
6. Ayers, J. H. 1985. Status and Outlook, U.S. Pesticide Industry. Am. Chem. Soc. (Abstract). Chicago, Illinois, September 9-12.
7. Batra, S. W. T. 1981. Biological Control of Weeds: Principles and Prospects. pp. 45-59. In G. C. Papavizas (ed.). Biological Control in Crop Production. Allanheld, Osmun & Co. Publishers, Inc., Totowa, New Jersey. 461 pp.
8. Brown, G. E., Jr. 1987. Getting to the New Age in Agriculture. Talk given to 6th Annual Meeting of the Industrial Biotechnology Association, October 23, 1987. 5 pp.
9. Carson, R. L. 1962. Silent Spring. Fawcett World Library, New York, New York. 304 pp.
10. Coates, J. F. 1979. What is a Public Policy Issue? Interdisciplinary Science Reviews 4(1):27-43.
11. Cook, R. J., L. Andres, G. A. de Zoeten, C. Doane, R. W. Gwadz, R. Hardy, B. Hemming, J. Kuc, R. Mankau, D. Miller, C. A. Ryan, Jr., and S. Smith. 1987. Report of the Research Briefing Panel on Biological Control in Managed Ecosystems. National Academy Press, Washington, DC. 12 pp.
12. Council for Agricultural Science and Technology. 1985. Agriculture and Groundwater Quality. CAST Report No. 103, Ames, Iowa. 62 pp.
13. Council on Environmental Quality. 1972. Integrated Pest Management. U.S. Government Printing Office, Washington, DC. 41 pp.
14. Day, B. E. 1978. The Status and Future of Chemical Weed Control. pp. 181-212. In E. H. Smith and D. Pimental (eds.). Pest Control Strategies. Academic Press, New York, New York. 334 pp.
15. Economic Research Service. 1983. Outlook and situation. IOS-2. USDA, Washington, DC. 13 pp.
16. Gianessi, L. P. 1987. Patterns of Pesticide Use in the United States: Results from the RFF National Pesticide Use Inventory. Resources for the Future, Washington, DC. 10 pp.
17. Hoy, M. A., and D. C. Herzog (eds.). 1985. Biological control in agricultural IPM systems. Academic Press, Orlando, Florida. 589 pp.
18. Kearney, P. C., A. R. Isensee, and J. R. Plimmer. 1988. Contribution of Agricultural Pesticides to Worldwide Chemical Distribution. In N. W. Schmidtke (ed.). Toxic Contamination in Large Lakes. Vol. III. Sources, Fate and Controls of Toxic Contaminant. Lewis Publishers, Inc., Chelsea, Michigan. pp. 49-60.
19. Klassen, W., J. R. Shay, B. Day, and A. W. A. Brown. 1975. Plant Protection from Pests. pp. 275-308. In A. W. A. Brown, T. C. Byerly, M. Gibbs, and A. San Pietro (eds.). Crop Productivity - Research Imperatives. Michigan Agricultural Experiment Station and C. F. Kettering Foundation. 399 pp.
20. Knipling, E. F. 1979. The Basic Principles of Insect Population Suppression and Management. Agriculture Handbook Number 512. USDA, Washington, DC. 659 pp.
21. Lindblom, C. E. 1968. The Policy-Making Process. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 122 pp.
22. Lyng, R. E. 1988. Alternative Farming Systems. Secretary's Memorandum 9600-1. January 19, 1988. 2 pp.
23. McWhorter, C. G., W. C. Shaw, and E. E. Schweizer. 1984. Present Status and Future Needs in Weed Control. USDA, ARS, Paper prepared for and submitted to Office of Technology Assessment. 20 pp.
24. Menn, J. J., and C. A. Henrick. 1985. Newer chemicals for insect control. pp. 247-265. In J. L. Hilton (ed.). Agricultural Chemicals of the Future, Beltsville Symposia in Agricultural Research, Vol. 8. Rowman and Allanheld, Totowa, New Jersey. 464 pp.
25. National Research Council, Committee on Diet, Nutrition and Cancer. 1982. Diet Nutrition and Cancer. National Academy Press, Washington, DC. 319 pp.
26. National Research Council, Board on Agriculture. 1987. Regulating Pesticides in Food: The Delaney Paradox. National Academy Press, Washington, DC. 272 pp.
27. Nielsen, G., and L. K. Lee. 1987. The magnitude and costs of groundwater contamination from agricultural chemicals: A national perspective. USDA, Economic Research Service, AER 576, Washington, DC. 38 pp.
28. Quimby, P. C., Jr., and C. D. Boyette. 1987. Production and application of biocontrol agents, pp. 265-280. In C. C. McWhorter and M. R. Gebhardt (eds.). Methods of Applying Herbicides. Weed Science Society of America, Monograph No. 4, Champaign, Illinois. 358 pp.
29. Quimby, P. C., Jr., and H. L. Walker. 1982. Pathogens and Mechanisms for Integrated Weed Management. Weed Sci. (Suppl.) 30:30-34.
30. Rawlins, S. L. 1984. Practices for Conserving Natural Resources and Minimizing the Impact of Agricultural Chemicals: Current State of the Art. pp. 92-103. In G. W. Irving, Jr. (ed.). Changing Agricultural Production Systems and the Fate of Agricultural Chemicals. Agricultural Research Institute, Rockville, Maryland. 160 pp.
31. Reichelderfer, K. H. 1981. Economic feasibility of biological control of crop pests. pp. 403-417. In G. C. Papavizas (ed.). Biological control in crop production. Allanheld, Osmun & Co. Publishers, Inc., Granada. 461 pp.
32. Reichelderfer, K. H. 1985. Factors affecting the economic feasibility of the biological control of weeds. In E. S. Delfosse (ed.). Proc. VI International Symposium on Biological Control of Weeds, Vancouver, Canada, August 19-25, 1984. pp. 135-144.
33. Ridgway, R. L. 1981. Biological pest control. In Yearbook of Science and the Future. Encyclopedia Britannica, Inc., Chicago, Illinois. pp. 92-105.
34. Rose, David J. 1981. Continuity and Change: Thinking in New Ways About Large and Persistent Problems. Technology Review, February/March. pp. 53-67.
35. Starler, N. H., and R. L. Ridgway. 1977. Economic and social considerations for the utilization of augmentation of natural enemies. In R. L. Ridgway and S. B. Vinson (eds.). Biological control by augmentation of natural enemies. Plenum Press, New York, New York. pp. 431-448.
36. Stern, V. M., R. F. Smith, R. van den Bosch, and K. S. Hagen. 1959. The Integrated Control Concept. Hilgardia 29:81:101.
37. Templeton, G. E., R. J. Smith, and D. O. TeBeest. 1986. Progress and Potential of Weed Control with Mycoherbicides. Rev. Weed Sci. 2:1-14.
38. U.S. Department of Agriculture. 1989. USDA research plan for water quality. ARS and CSRS in cooperation with State Agricultural Experiment Stations. ARS, Beltsville, Maryland. 15 pp.
39. Whitten, J. L. 1966. That We May Live. D. Van Nostrand Co., Inc., Princeton, New Jersey. 251 pp.

Bulletin board service organized by Acres U.S.A.

A computerized bulletin board listing organic foods available on the market is now operated by Acres U.S.A. for its members. Listings cost $1 a day, with a 20-day minimum listing. Wholesalers and other buyers will be able to tap into the bulletin board with their computers 24 hours a day, seven days a week, says Acres. For more information, contact Acres U.S.A., P.O. Box 9547, Kansas City, MO 64133, (816) 737-0064.

COMMENTARY

Research and extension agenda for sustainable agriculture

Charles A. Francis, James W. King, Darrell W. Nelson, and Leo E. Lucas

Key words: soil productivity, hybrids, varieties, lowered inputs, cultural practices, producer profits

Today's farmers are searching for resource-efficient, lower-cost, and more profitable production systems. Everyone in agriculture shares the broader concerns of society for a clean and livable environment. One logical strategy is to reduce chemical and fertilizer inputs to those minimum levels needed by crops which will give consistent and profitable response. Coupled with this strategy is more intensive management of internal resources on the farm. Research and extension can play a pivotal role in the process we call an agenda for sustainable agriculture. Future farming practices need to minimize the immediate problems of soil erosion and ground water contamination and sustain soil productivity through stewardship of our vital land resource. A "sustainable agricultural system" can be defined as a *management strategy* which helps the producer to choose hybrids and varieties, soil fertility programs, and the cultural practice package including rotations, tillage and crop sequences to *reduce costs of purchased inputs, minimize the impact* of the system on the immediate and the off-farm environment, and provide a *sustained level of production and profit* from farming (Agronomy Department, UNL, 1987).

This working definition helps us decide which research results are most relevant to include in extension meetings and promotional materials. Based on questions over the past several years, we know that producers are searching for ways to reduce costs of production. There are serious and legitimate concerns about the off-farm environmental effects of current practices as well as effects on health and safety of farm families. Specific farming practices useful to meet these concerns are given in a recent article in Crops and Soils magazine: "Search for a Sustainable Agriculture...Reduced Inputs and Increased Profits" (Francis et al., 1987).

The search for rational alternatives is taking place in a climate of depolarization in agriculture. Environmental groups and agribusiness leaders once produced statements viewed as "extremist" in the other camp. Today there is greater communication and accommodation toward a future which satisfies a broad range of human needs within our political and economic system. For example, progressive agricultural chemical manufacturers and dealers now appreciate the need for judicious use of their products, and research priorities are established to meet this goal. We need to choose among available technologies and determine which ones are appropriate for the future.

Choice of component technologies

A new emphasis on sustainable agriculture does not mean going back 50 years to a less complicated agriculture. Nor does it mean starting over in research and extension. Much of our component technology research has direct application in reducing costs of purchased inputs. Breeding crops for insect and disease tolerance or resistance can drastically reduce the need for pesticides. Incorporating drought tolerance reduces the need for irrigation and reduces risk of crop loss. Integrated pest management has been an objective of research and extension programs for about two decades. Reduced tillage systems and improved planting equipment have introduced new potentials for moisture conservation and reduction of erosion on susceptible lands. Benefits of rotations are becoming better understood, as they contribute to soil fertility and pest control. Potential developments in biotechnology may open windows of opportunity in crop productivity and plant protection that we cannot yet conceive. Thus, the current research and extension agenda provides some of the needed component technology. There is a growing awareness of the importance

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of integrating components into cropping systems which can reduce need for purchased inputs and make maximum use of internal resources on the farm (Rodale, 1985).

Agenda for research

One needed dimension for future research is a continued search for practices which reduce input costs. Fine-tuning fertilizer recommendations and calibration of soil test results with field responses of crops are examples of current research which needs to be intensified in some areas of the country. Use of weed indices to determine crop yield decline threshholds and levels of economic damage can be helpful to producers who seek rational decisions on the type of weed control which is economical in the short run as well as sustainable. Breeding solutions to pest or moisture stresses provide a low-cost approach which can substitute a modified genetic package for chemical controls or costly irrigation. Genetic solutions may be environmentally more benign and economically more sustainable than petro-chemical solutions. Conscious decisions to encourage more practical research to reduce inputs can stimulate the search for components of a sustainable agriculture.

More important than these components, individually or collectively, is the focus on cropping and farming systems. Most of the easy solutions with single component technologies have been found and some have been implemented. We are faced today with more complex problems. Many of tomorrow's advances will be found in the interactions among factors, at the interface between disciplines, and in the combination of elements in new systems which we can only understand by manipulating large amounts of information. Use of expert systems and computer-aided decision making will be a part of these solutions. Simulation of cropping systems and whole farm models can be useful to sort out a wide range of options before implementing the costly phase of field testing. It is likely that we will find creative combinations of conventional farmer wisdom and new components of technology -- some would call this "common sense use of new scientific facts and technology." But we need to test these ideas on farms. One role of the Cooperative Extension System will be increased involvement in direct testing of technology with farmers.

Validation and demonstration of technology

Over the years the research-extension-production continuum has often been considered a one-way street by many in the research system. Problems have been identified by investigators, sometimes in consultation with extension specialists or a few key producers, and research has been accomplished within the bounds of the experiment station. Off the experiment station, we have often transplanted conventional research designs into another environment under control of the researcher. Examples are uniform variety tests, multi-level fertility trials, and screening of herbicides under a range of conditions. Whether on-station or on-farm, this approach has provided valuable small plot data to researchers.

Extrapolating from this research base, we have prepared extension bulletins, fact sheets, and workshops for our county agents and state specialists to move information to producer clients and industry. Although there is some feedback from producers through extension agents and specialists to those who make research decisions, our system generally is characterized by the "top down" model of setting priorities and searching for alternatives in the design of treatments in practical research trials. When problems with single crops are obvious and when the most limiting constraints are widely known, this model can be successful in getting answers and moving them out to clients.

As problems in agriculture become more complex, however, the model becomes less valuable. We need to search for alternative approaches which are more broadly based, to bring in more ideas and broaden the ownership of the research agenda. Working as a team, producers, extension agents/specialists, and researchers can identify priority areas where more information is needed and together can search for a range of alternative solutions. Each of the players brings certain talents to the game - farmers have practical experience and have tried some alternatives in the past, extension agents and specialists have worked with a number of farmers and have additional solutions in mind, and researchers know what can be answered through research with an appropriate design and analysis. All the actors have a role in the interpretation of results.

This model builds on experience in the International Agricultural Research Centers where such programs have been called "Farming Systems Research and Extension" (Gilbert et al., 1980). Farmer involvement is a key link in the research process. This agenda includes joint farmer-researcher identification of researchable questions and new practices to test, sorting of potential solutions and testing on farm, and validation of results and extension of information to others in the immediate area. A project using soybeans as a model system is now being implemented in South Central Nebraska with farmer participation. Another project focusing on efficient nitrogen use and potentials for alternative cropping systems was begun in 1988 in the eastern portion of Nebraska. These projects lead to practical baseline data which can be used in crop-specific as well as whole-farm models. The next step can be sophisticated and powerful simulation research which is based on practical results and a close collaboration of extension agents and farm operators. Expert systems can make the management tools available to a wide range of farmers throughout the state. Integration of ideas, energies, and resources will be a viable alternative to the current research and extension agenda which is built entirely on public and grant support and which follows the one-way street described above.

Importance of local ownership

Much success in extension programs is due to the strength of county organizations and the participatory identification which communities feel toward extension. This system has served agri-

culture well over the decades, in 4-H programs, fairs, demonstration activities, dissemination efforts, and other pursuits. It is time to build a strong identity and sense of identification with programs which focus on sustainable agriculture. Conservation tillage trials and demonstrations in Nebraska have been exemplary in their involvement of a large number of people in each district. Demonstration plots of alternative crops have involved both farmers and lending institutions. When farmers and others in the community participate in choosing components and in deciding which systems to test, local interest in the project is high from the beginning. The potential adoption of sustainable agricultural practices is encouraged.

When county extension staff participate in problem identification, finding collaborators to work with a specific project, identifying resources, and taking data in the field, they also have a part of this ownership. If this joint effort is considered a part of the core program in the county, and the results are recognized as a key part of their contribution to the annual work plan, then quality time will be spent on projects and valuable results can come from the activity. If the project is seen as one more "add-on" to an already busy program, then it is likely to be put on the back burner. We need all the players involved and all the players need to be enthused about the potential outcome of the effort. It is important to analyze the reward system of each of the key people in this process, and be sure that each has a unique role to play. The result is a true community effort.

Extension in the future: Balance and diversity

There is no question about the need for Extension to continue to address the multiple challenges of today's crops and systems. There is also no doubt that we need to pursue new directions in order to help our industry adapt to future changes in resource availability and societal awareness of environmental issues. These concerns already impact farming. What is needed in Extension is balance, diversity, and an ability to adapt to changes which we perceive as useful in helping agriculture be sustainable into the future -- as well as profitable and ecologically viable in the short run. Here is a perspective for Extension which can promote a sustainable agriculture:

-- focus on *systems rather than components*: many of the advances possible through introduction of a single component into a farming enterprise have been made; future advances often will require an appreciation of the entire system and the interactions among component crops and crops with the environment.

-- focus on *internal resources*: whenever production inputs found on the farm or in the local community can be substituted for purchased or non-renewable inputs, there is likely to be greater efficiency and profitability in the system.

-- focus on *information as a key production input*: wherever information can be substituted for a purchased input, greater resource use efficiency may result and the production system can become more sustainable for the future.

-- focus on *participatory systems for developing information*: on-farm research and validation options need to be explored, where producers and local extension people become full participants in the research process and feel ownership of the research agenda.

-- focus on *process rather than product*: we have a generation of producers who seek a "formula" or "product in a package" to solve most production constraints; we need to stress the importance of evaluating a series of alternative solutions as well as understanding the entire farming enterprise and environment and the process needed to solve problems in the system, as opposed to spraying or applying a product as the only alternative.

-- focus on *diversity of enterprises and products*: the importance of both biological and economic diversity needs to be stressed; at the expense of becoming less an expert on one or two crops, some successful managers in the future will explore more options on farm and value-added activities.

-- focus on *community as well as on farming*: viable communities are critical to the long-term success of a viable agriculture; value-added industries based on locally produced agricultural products can bring jobs and vitality to communities.

-- focus on *value-based decisions*: as opposed to letting new technology set the agenda for the future, we need to empower people to make their own rational decisions about the use of this technology; there are some components which may logically sit on the shelf, while others are rapidly incorporated into a farming system. Rural families and communities need to examine their own needs and goals, and carefully search out an approach which will help them to meet these goals, consistent with the available resource base.

In Extension we are but one part of the team in agriculture. We need critical linkages with the farmer and rancher, with agricultural industry, and with other organizations. We need to objectively explore diverse approaches which are advocated by a wide range of players. Information is a key component in these approaches. Sharing ideas among farmers and across state lines can be valuable. A recent conference on sustainable agriculture stressed this exchange (Univ. Nebraska, 1988).

If the Cooperative Extension System can successfully participate in this process, we have a bright future. The chance to implement the new national priorities within the context of each state's specific agenda brings an opportunity for change. There will be funding attached to these priorities, and thus an additional stimulus for states to adapt their programs, but the most important resources are those already in each state. And the most critical resource is the human one. Our orientation of programs and plans to take advantage of the creativity which exists in each family and rural community will serve agriculture well in the future. Resulting programs and activities in research and extension can help to catalyze this process, and the result can be a more sustainable agriculture and more viable rural economy.

References

1. Agronomy Department, UNL. 1987. Sustainable Agriculture...Wise and Profitable Use of

Our Resources in Nebraska. Cooperative Extension Service, IANR, Univ. of Nebraska, Lincoln. Special Publication. 220 pp. (Available by mail for U.S. $7).
2. Francis, C., D. Sander, and A. Martin. 1987. Search for a Sustainable Agriculture: Reduced Inputs and Increased Profits. Crops & Soils, Aug.-Sept. pp. 12-14.
3. Gilbert, E. H., D. W. Norman, and F. E. Winch. 1980. Farming systems research: a critical appraisal. MSU Rural Development Paper No. 6, Dept. of Agr. Econ., Michigan State Univ., East Lansing, Michigan.
4. Rodale, R. 1985. Internal resources and external inputs: The two sources of all production needs. Workshop Rept. on Regenerative Farming Systems, Washington, DC, Dec. 10-11, USAID. Publ. by Rodale Inst., Emmaus, Pennsylvania.
5. Univ. of Nebraska. 1988. Sustainable agriculture in the Midwest. Proc. North Central Regional Conference, March 22, Lincoln Nebraska. 102 pp.

INSTITUTE NEWS

Keeney to address IAA symposium

Dennis Keeney, Director of the new Leopold Center for Sustainable Agriculture at Iowa State University, will give the keynote address on "Concepts and Components in Sustainable Farming Systems" at the February 28, 1989, Institute Symposium. The overall theme of the one-day symposium, to be held in Washington, DC, is "Sustainable Farming Systems: Needs and Opportunities."

Following Keeney's talk, Frederick Kirschenmann, an organic farmer from Windsor, North Dakota, will provide a viewpoint on "Low-Input Farming in Practice." David Bezdicek of Washington State University will speak on crop rotations in low-input systems, and Frank Baker of Winrock International will outline the role and potential of animal agriculture in integrated low-input farming systems. Richard Harwood of Winrock International will moderate the sessions on diversified systems.

In afternoon sessions, policy considerations related to sustainable farming will be addressed by two panels including Sandra Batie of Virginia Polytechnic and State University, Douglas Young of Washington State University, John E. Lee of the USDA Economic Research Service, Charles Benbrook of the National Science Foundation Board on Agriculture, Ken Cook of the Conservation Foundation, and Ron Kroese of the Land Stewardship Project. The two panels will be moderated by Otto Doering of Purdue University and Maureen Hinkle of the National Audubon Society.

For information on the symposium, contact the Institute.

Bender, Liebhardt, Ohrstrom, and Watkins elected to IAA board

Four new directors, who bring wide experience in alternative agricultural research, education, farming, and business, were elected to the Board of the Institute for Alternative Agriculture at its September 10th meeting in Davis, California. James Bender, from Weeping Water, Nebraska, is a farmer, writer, and board member of the Nebraska Sustainable Agriculture Society. William Liebhardt directs the Sustainable Agriculture Program at the University of California-Davis and was formerly the assistant director of the Rodale Research Center. Per Bye Ohrstrom is owner of P. O. Ohrstrom & Sons and Maxicrop U.S.A., two seaweed product companies in Arlington Heights, Illinois. Gordon Watkins is owner of Rivendell Gardens and its associated Greengrocery in Arkansas as well as president of the Ozark Organic Growers Association. The four will join the IAA Board at its March, 1989, meeting.

The Board also set in motion a long-range planning process and approved the 1989 Symposium plans. Following its meeting, the directors visited the Ed Sills 1,200-acre organic rice/popcorn/almond farm north of Sacramento. The group also traveled to the University of California's agroecology farm in Santa Cruz. The 17-acre farm has diverse cropping areas, including an aquaculture wastewater treatment system, and is the site of the world-renowned Alan Chadwick organic garden. Agroecology Program Director Steve Gliessman led the tour.

"Meeting in California allowed the Institute Board to learn more about the status and direction of sustainable agriculture in that important state," says Jim Lukens, President of the Board.

IAA co-sponsors low-input, organic conferences

The Institute is co-sponsoring two national conferences this spring. The first, with the Soil and Water Conservation Society and others on March 8-10 in Omaha, Nebraska, is "The Promise of Low-Input Agriculture: A Search for Sustainability and Profitability." Its purpose is to look at ways to incorporate sustainable, low-input production practices into conventional farming systems. The meeting is designed for technicians at all levels of government--those who advise farmers directly and those who work on long-range policy.

The second conference, co-sponsored with the Center for Science in the Public Interest and to be held March 16-17 in Washington, DC, is the National Conference on Organic/Sustainable Agriculture. This conference will have sessions on such topics as standards for organic foods, marketing efforts, the economics of organic/sustainable farming, and its policy needs.

For further meeting information, see the list of Upcoming Events in this Journal.

IAA joins Natural Resources Council

In November, 1988, the Institute became a member of the Natural Resources Council of America, a national group centered in Washington, DC, which fosters cooperative efforts to promote adoption of public policies to protect the environment. Over 60 national groups comprise the membership of the NRCA, including such diverse groups as the National Wildlife Federation and the American Farmland Trust, the Alliance for Environmental Education and the Society for Range Management.

NRCA programs include a monthly round table on environmental issues, multiple task forces designed to help members work together on specific policy areas, Congressional/executive breakfasts, briefings, and numerous publications on information of broad use to its institutional members. The Institute views this membership as part of its effort to share information on alternative agriculture with a broad range of other national groups and to strengthen efforts of such groups to find sound solutions to resource degradation problems related to agriculture.

Congress votes $4.45 million for low-input in '89

Low-input farming research and education were named for $4.45 million in the FY1989 budget passed by Congress and signed by the President on October 1. That is a half-million more than the $3.9 million appropriated for the program in 1988. The figure is a mid-point compromise between the House recommendation of $3.9 million and the Senate proposal for $5 million, but it is well under the $15 million figure suggested by the Institute for Alternative Agriculture and other supporters of the program. Funds will continue the grants program for whole-system, low-input projects which got underway this past summer.

The program got an upbeat review at a September conference called to gather viewpoints on its 1988 track record and to make recommendations for its future. "If we didn't have this program, we'd have to start it," commented House Agriculture Committee staffer Skip Stiles. IAA Executive Director Garth Youngberg summed up the assets of the 1988 program. "Open participation was genuine, USDA and land-grant involvement in low-input agriculture through this program helped create a positive climate for the work, and the timing was propitious," he said. "A strong coalition of consumers, environmentalists, and farmers is interested in the direction of low-input farming."

For information on the '88 projects or the proposal process for 1989, contact the following: *Northeast Region*: **Fred Magdoff**, Department of Plant and Soil Science, Hills Building, University of Vermont, Burlington, VT 05405, (802) 656-2630; *Southern Region*: **Charles Laughlin**, Agricultural Experiment Station, University of Georgia, Athens, GA 30602, (404) 542-2151; *North Central Region*: **Warren Sahs**, Agricultural Experiment Station, University of Nebraska, Lincoln, NE 68583, (402) 472-2973; *Western Region*: **David Schlegel**, Division of Agriculture & Natural Resources, University of California, 300 Lakeside Drive, 6th Floor, Oakland, CA 94612-3560, (415) 987-0029; *Cooperative State Research Service*: **Patrick Madden**, CSRS-OSPPS, USDA, Washington, DC 20250-2200, (202) 447-3640; **Dixon Hubbard**, ES-USDA, 3851 South Building, Washington, DC 20250-0990, (202) 447-2677.

Sustainable agriculture association formed in Indiana

At a charter meeting on November 1, Hoosier supporters of sustainable agriculture gathered in Indianapolis to form the Indiana Sustainable Agriculture Association (ISAA). Dave Swaim, a crop consultant from Crawfordsville, Indiana, was elected president of the group. Other officers and directors include farmers, researchers, extension agents, and state representatives.

Agriculture in the future will require the balancing of economic, ecological, and social concerns," the ISAA statement says. Its founders see the association as a way to increase public awareness of progress in sustainable agriculture, encourage good research, facilitate adoption of sustainable techniques on Indiana farms, and encourage a spirit of cooperation among farm, business, research, and environmental and regulatory groups.

For the future, look for meetings, field days, formation of local support groups, and publication of a newsletter, the group says. For more information, contact Dave Swaim, 807 South Green, Crawfordsville, IN 47933.

COMMENTARY

Sustainability is not enough

Vernon W. Ruttan

Abstract. *Traditional agricultural systems that have met the test of sustainability have not been able to respond adequately to modern rates of growth in demand for agricultural commodities. A meaningful definition of sustainability must include the enhancement of agricultural productivity. At present, the concept of sustainability is more adequate as a guide to research than to farming practice.*

Key words: sustainability definition, productivity increase, population growth, income increase, research implications

Any definition of sustainability suitable as a guide to agricultural practice must recognize the need for enhancement of productivity to meet the increased demands created by growing populations and rising incomes. The sustainable agricultural movement must define its goals sufficiently broadly to meet the challenge of enhancing both productivity and sustainability in both the developed and developing world. I will illustrate the problems of achieving these goals with some historical examples.

Ambiguity about technology

The productivity of modern agriculture is the result of a remarkable fusion of science, technology and practice. This fusion did not come easily. The advances in tillage equipment and crop and animal husbandry which occurred during the Middle Ages and until well into the 19th century evolved almost entirely from husbandry practice and mechanical insight. The power that the fusion of theoretical and empirical inquiry has given to the advancement of knowledge and technology since the middle of the 19th century has made possible advances in material well-being that could not have been imagined in an earlier age.

These advances have also been interpreted as contributing to the subversion of traditional rural values and institutions and to the degradation of natural environments. They led, in the 1960s and 1970s, to the emergence of a new skepticism about the benefits of advances in science and technology. A view emerged that the potential power created by the fusion of science and technology is dangerous to the modern world and the failure of the human race.

This ambiguity about the impact of science and technology on institutions and environments has led to a series of efforts to increase the sensitivity of scientists and science administrators and to reform the decision processes for the allocation of research resources. These efforts have typically attempted to find rhetorical capsules which would serve as a banner under which efforts to achieve reforms might march. Among the more prominent have been "appropriate technology," "integrated pest management," "low-input technology" and, more recently, "sustainability."

Reforming agricultural research

It is not untypical for such rhetorica capsules to achieve the status of an ide ology or a social movement while sti in search of a methodology, a technol ogy, or even a definition. If the reform movement is successful in directing sci entific and technical effort in a produc tive direction, it becomes incorporate into normal scientific or technologica practice. If it leads to a dead-end, it slip into the underworld of science often t be resurrected when the condition which generated the concern agai emerge toward the top of the socia agenda.

Research on new uses for agricultura products is an example. It was promote in the 1930s under the rubric of che murgy and in the 1950s under the rubri of utilization research as a solution t the problem of agricultural surpluses. I lost both scientific and political credi bility because it promised more than i could deliver. It has emerged again, i the late 1970s and early 1980s, in th guise of enhancing value added.

The "sustainability" movement, lik other efforts to reform agricultural re search, has experienced some difficult in arriving at a definition that can com mand consistency among the diverse an sometimes incompatible reform move ments that are marching under its ban ner. Those of you who may recall th more populist conservation literature o the 1950s, such as *Topsoil and Civil zation* (1955) by Tom Dale and Verno Carter, or *Malabar Farm* (1947) b Louis Bromfield, will recognize the po etry that has emerged in some of th

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new sustainability literature. Fortunately we can draw on several historical examples of sustainable agricultural systems.

Sustainable agricultural systems

One example of sustainable agriculture was the system of integrated crop-animal husbandry that emerged in Western Europe in the late middle ages to replace the medieval two- and three-field systems (Boserup, 1965). The "new husbandry" system emerged with the introduction and intensive use of new forage and green manure crops. These in turn permitted an increase in the availability and use of animal manures. This permitted the emergence of intensive crop-livestock systems of production through the recycling of plant nutrients in the form of animal manures to maintain and improve soil fertility.

A second example can be drawn from the agricultural history of East Asian wet rice cultivation (Hayami and Ruttan, 1985). Traditional wet rice cultivation resembled farming in an aquarium. The rice grew tall and rank; it had a low grain-to-straw ratio. Most of what was produced, straw and grain, was recycled into the flooded fields in the form of human and animal manures. Mineral nutrients and organic matter were carried into and deposited in the fields with the irrigation water. Rice yields rose continuously, though slowly, even under a monoculture system.

A third example is the forest and bush fallow (or shifting cultivation) systems practiced in most areas of the world in pre-modern times and today in many areas of tropical Africa (Pingali, Bigot and Binswanger, 1987). At low levels of population density, these systems were sustainable over long periods of time. As population density increased, short fallow systems emerged. Where the shift to short fallow systems occurred slowly, as in Western Europe and East Asia, systems of farming that permitted sustained growth in agricultural production emerged. Where the transition to short fallow has been forced by rapid population growth, the consequence has often been soil degradation and declining productivity.

Sustaining and enhancing productivity

This brings me to the title of this paper. The three systems that I have described, along with other similar systems based on indigenous technology, have provided an inspiration for the emerging field of agroecology. But none of the traditional systems, while sustainable under conditions of slow growth in demand, has the capacity to respond to modern rates of growth in demand generated by some combination of rapid increase in population and in growth of income. Some traditional systems were able to sustain rates of growth in the 0.5-1.0 percent per year range. But modern rates of growth in demand are in the range of 1.0-2.0 percent per year in the developed countries. They often are in the range of 3.0-5.0 percent per year in the less developed and newly industrializing countries; rates of growth in demand in this range lie outside of the historical experience of the presently developed countries!.

In searching the literature on sustainability, I do not find sufficient recognition of the challenge that modern rates of growth in demand impose on agriculture. If the concept of sustainability is to serve as a guide to practice, it must include the use of technology and practices that both sustain and enhance productivity.

In the United States, the capacity to sustain the necessary increases in agricultural production will depend largely on our capacity for institutional innovation. If we lose our capacity to sustain growth in agricultural production, it will be a result of political and economic failure. Failure to reform agricultural commodity programs in a manner that will contribute to both sustaining and enhancing productivity will mean the loss of one of the few industries in the United States that has managed to retain world-class status--that is capable of competing in world markets (Ruttan and von Witzke, 1988).

It is quite clear, however, that the scientific and technical knowledge is not yet available that will enable farmers in most tropical countries to meet the current demand their societies are placing upon them nor to sustain the increases that are currently being achieved. Further, the research capacity has not yet been established that will be necessary to provide the knowledge and the technology. In these countries, achievement of sustainable agricultural surpluses is dependent on advances in scientific knowledge and on technical and institutional innovation.

Implications for research

I am deeply concerned that the commitment to support the development of the research capacity in both developed and developing countries that will be necessary to achieve productive and sustainable agricultural systems has been weakening. And I am also concerned that the sustainability movement is pressing for adoption of agricultural practices under the banner of sustainability before either the science has been done or the technology is available.

It has been surprisingly difficult to find careful definitions of the term sustainability. This is at least in part because "sustainability," if it is to provide a useful rhetoric for reform, must be able to accommodate the several traditions that must march under its banner. These include the organic agriculture tradition, the land stewardship movement, the agroecology perspective, and others. In my judgment, any attempt to specify the technology and practices that meet the criteria of sustaining and enhancing productivity would be premature. *At present it is useful to define sustainability in a manner that will be useful as a guide to research rather than as an immediate guide to practice.* As a guide to research, it seems useful to adhere to a definition that would include (a) the development of technology and practices that maintain and/or enhance the quality of land and water resources, and (b) the improvement in plants and animals and the advances in production practices that will facilitate the substitution of biological technology for chemical technology.

Furthermore, it is desirable to generate the knowledge that will enable us to determine what it is possible to achieve in the direction of the above objectives primarily from a biological perspective. Maximum yield experiments represent a useful analogy. The objective of a maximum yield experiment or trial is not to provide a guide to farm practice. Rather it is to find out how a plant population performs under high level input stress. *The research agenda on sustainable agriculture needs to define what is biologically feasible without being excessively limited by present economic constraints.*

References

1. Boserup, E. 1965. Conditions of Agricultural Growth. Aldine Publishing Company, Chicago, Illinois.
2. Bromfield, L. 1947. Malabar Farm. Harper, New York, New York.
3. Dale, T., and V. G. Carter. 1955. Topsoil an Civilization. Oklahoma University Press, No man, Oklahoma.
4. Hayami, Y., and V. W. Ruttan. 1985. Agr cultural Development: An International Pe spective. The Johns Hopkins University Pres Baltimore, Maryland. pp. 280-298.
5. Pingali, P., Y. Bigot, and H. P. Binswange 1987. Agricultural Mechanization and the E olution of Farming Systems in Sub-Saharan A rica. The Johns Hopkins University Pres Baltimore, Maryland.
6. Ruttan, V. W., and H. von Witzke. 1988. To ward a Global Agricultural System. Interdi ciplinary Science Reviews (in press).

IAA and sixty organizations write George Bush

At the suggestion of IAA board member Robert Blake, the Institute has sent President-Elect George Bush a letter calling his attention to the promise and policy needs of low-input sustainable agriculture. The letter was co-signed by sixty national organizations (see list below).

"Dear Mr. President-Elect: You take office during a time of great change in our American agricultural economy," the letter says. It outlines both the economic and environmental problems of agriculture to which low-input methods provide one effective response. While citing the value of the new Low-Input Sustainable Agriculture Research Program (LISA) at the USDA, it calls for further action.

"We need to take an in-depth look at ways of integrating these production methods into the overall structure of farm policy and USDA research and education programs," the letter says. Specifically, it suggests changes in farm commodity programs to encourage more environmentally sound practices; an insurance program to help farmers through the risk of transition periods; and more research and adequate information flow to farmers on new low-input approaches to farming.

"We need to launch a full-fledged, across-the-board program at the Department of Agriculture to overcome obstacles and open pathways to developing the potential of low-input alternatives," the letter concludes. "We are convinced that the price tag for such a program will be low and the results positive and cost-effective. We are also convinced that this direction offers the best opportunity for American agriculture to become a more sustainable part of our total economy and leave for the generations to come an even richer base of unpolluted water and soils." The letter was mailed on December 6.

1. Alternative Energy Resources Organization
2. American Environmental Health Foundation/Environmental Health Center-Dallas
3. American Farmland Trust
4. Appropriate Technology Transfer for Rural Areas
5. Bio-Dynamic Farming and Gardening Association
6. Bread for the World
7. California Certified Organic Farmers
8. California Institute for Rural Studies
9. Carolina Farm Stewardship Association
10. Center for Science in the Public Interest
11. Center for Respect of Life and Environment/ The Humane Society of the U.S.
12. Center for Rural Affairs
13. Citizens for Alternatives to Chemical Contamination
14. Clean Water Action
15. Clearinghouse for Community Economic Development
16. Concern
17. Cornucopia Network of New Jersey
18. Farm Verified Organic
19. Friends of the Columbia
20. Institute for Alternative Agriculture
21. Iowans for Organic Food Standards
22. Jessie Smith Noyes Foundation
23. Kansas Organic Producers
24. Kansas Rural Center
25. The Land Institute
26. Land Stewardship Project
27. Maine Organic Farmers and Gardeners A sociation
28. Massachusetts Audubon Society
29. National Audubon Society
30. National Center for Appropriate Technolog
31. National Farmers Organization
32. National Network to Prevent Birth Defects
33. National Wildlife Federation
34. Natural Food Associates
35. Natural Organic Farmers Association of Ma sachusetts
36. Natural Resources Defense Council
37. New Alchemy Institute
38. Northern Plains Sustainable Agriculture S ciety
39. Northwest Coalition for Alternatives to Pe ticides
40. Ohio Ecological Food and Farm Associatio
41. Organic Growers and Buyers Association
42. Ozark Organic Growers Association
43. Pesticide Education and Action Project
44. John P. Powers and Company
45. Practical Farmers of Iowa
46. Renew America
47. Rocky Mountain Institute
48. Rural Coalition
49. Rural Economic Policy Program/Aspen I stitute
50. Rural Virginia
51. Ruth Mott Fund
52. Seattle Tilth Association
53. Shalan Foundation
54. Sierra Club/Agriculture Issues Committee
55. Society for Range Management
56. Texas Department of Agriculture
57. Texas Organic Growers Association
58. Wildlife Habitat Charitable Trust
59. Winrock International/Institute for Agric tural Development
60. Wisconsin Rural Development Center

Public Policy and Agricultural Technology. 1987. Edited by Don F. Hadwiger and William P. Browne. The MacMillan Press, Ltd., Houndmills, Basingstoke, Hampshire RG21 2XS and London. 126 pp.

As stated in the Preface, "This book was written at an exceptionally dramatic and paradoxical time in the history of agricultural research. Nations throughout the world are on the verge of rapidly expanding food production for numerous basic commodities. At the same time, however, farmers and national economies are already being damaged by the problems of food surplus on an international scale. Agricultural research, playing center stage in this world food situation, has become both a miracle worker and villain in the eyes of many."

This book is divided into four parts, each having two chapters. In the introductory chapter, the editors explain current conditions affecting agricultural research. They document the decline in funding for public agricultural research in the U.S., as well as in some developing countries and including the International Agricultural Research Centers. Reasons given for this decline in support are: 1) loss of representation and strategic power positions in the agricultural sector; 2) research funding is politically controversial; 3) research politics is moving from a distributive "pork barrel" process to a redistributive budget recission process; 4) agricultural research is relatively unsheltered in the budget process and becomes vulnerable to budget cuts; 5) the class of innovative farmers who were the principal users of research has been depleted.

In the second chapter, Alan I. Marcus presents an overview of the history of public agricultural research institutions in America. He explains that support for agricultural research in the U.S. has not come from "society" but from complex interaction between farmer groups and scientist groups. Prior to the 1870's, American farmers did virtually all their own research, largely through the media of agricultural newspapers and societies. Farmers deprecated the agricultural colleges for not pursuing their interests in maximizing productivity and production. Passage of the Hatch Act in 1887 and new USDA initiatives established a *de facto* national system of agricultural research. This model has been duplicated worldwide.

Part II is entitled "Thinking about agricultural and research alternatives." Carlisle Ford Runge argues the need to consider alternatives. He notes that recent financial problems in agriculture result from investments in high technology, capital-intensive farming. Runge provides evidence that technology, *per se*, is less important than financial forces in explaining structural change in agriculture. Farm size has increased because the opportunity cost of machinery was less than that of labor. This relationship was reversed in the 1970's. However, financial advantages continued to benefit larger farmers. Current policy does not provide for corrective actions, thereby forcing many of the best educated and most technically proficient farmers out of business.

In chapter 4, Garth Youngberg encourages a systems approach to agricultural production, suggesting that low-input systems may be more sustainable in an age of agricultural abundance and environmental pollution. He argues for a balance without retreating solely to organic farming, since such a position would doom alternative agriculture. Prospective changes may make low-input agriculture more viable. These changes include the possible repeal of federal tax and credit policies which encouraged capital-intensive farming; new consumer attitudes favoring chemical-free food, and emerging environmental measures which, for example, tax fertilizers and pesticides as a means of paying for environmental damages. Finally, reduced demand for food exports, as other nations produce their own food, may mean reduced incentives for high-input technologies.

Part III discusses current political issues and conflict and attempts to answer whether policy makers will respond. In chapter 5, Hemchandra Gajbhiye and Don Hadwiger examine the present basis of political support for high technology research, both national and international. They outline the need for international agricultural research, pointing out that direct transfer of technology to the developing countries is not practical due to different climates, soils, as well as unique social conditions. Among the low income countries, the relative amount of money spent on agricultural research is considerably less than in the middle and high income countries. The authors describe the establishment of the Consultative Group on International Agricultural Research (CGIAR) supporting the network of International Agricultural Research centers. Economic rates of return from investments in research are cited. Even though these returns are high, there is need to more clearly articulate the overall benefits for public support of research. The authors conclude that the U.S. agricultural system and international research centers are complementary in their efforts to develop support for their own missions. The international centers enhance the legitimacy of all agricultural research.

In chapter 6, W. Browne examines the array of interests and arguments critical of agricultural research in the 1980's. These include questions on the costs of research and the program beneficiaries, i.e., often large corporate farms as opposed to low income farm families; product quality and safety; and environmental considerations. The authors state that critics of agricultural

research represent a cross-section of interests involved in policy making. Included are farm protest groups formed in response to the depressed farm economy; traditional farm organizations; and market-oriented firms and other associations. They conclude that there is no evidence that these critics are allied against agricultural policy. Instead, their demands vary widely and frequently run counter to one another. Their potential negative effects are 1) fragmentation of agricultural research projects and programs among a greater number of targeted clientele, with resultant dilution of present research efforts; and 2) diminished credibility of agricultural researchers and political supporters and subsequent erosion of funding.

The final section of the book is entitled "The Prospects for Agenda Change." J. Patrick Madden, in chapter 7, challenges the agricultural academe, from economists to agronomists, to address the implications of their work, since they are in the best position to do this. At one time, the only criterion for selecting research projects was whether they promoted efficiency. Madden points out that social and ecological side effects often occur after a technology has been used. He suggests that the research institutions should adopt a "new covenant," committing themselves to be "scientifically excellent, socially relevant, and ecologically responsible." Fortunately, new legislative mandates and governing mechanisms are moving agencies toward such a commitment. Agricultural research agencies will gain wider acceptance or legitimacy as they demonstrate their determination to avoid unwanted side effects. They will also persuade others that these side effects are best remedied by improving technology rather than by retreating from modern agriculture. Madden discusses in some depth the issue of private industry, particularly chemical companies, influencing land-grant agricultural research.

In chapter 8, Frederick H. Buttel and Martin Kenny examine prospects for biotechnology for meeting the enormous food needs in developing countries. The authors point out that biotechnology is relatively inexpensive and thus potentially accessible to most developing nations. In fact, LDC's could become producers--and hence controllers of the research agenda--as well as consumers of the technology. However, much biotechnology research is now in the private sector, and there is concern that private companies might deny its benefits to those who cannot afford to buy it. The big industrial input companies will seek to control technology through gaining patents, as in their current move to purchase seed companies. Since the companies are market oriented, they will seek large markets in a few developing countries while ignoring other areas. The authors suggest that the governments of the developing countries could form public corporations as vehicles to deliver this technology.

In conclusion, this relatively small book contains many valuable insights into the social, political, economic, and institutional problems associated with agricultural technology. -- *Norman Ulsaker, Consultant, Institute for Alternative Agriculture, Greenbelt, MD.*

Resourceful Farming, a Primer for Family Farmers. 1987. Center for Rural Affairs, Walthill, Nebraska. 118 pp. $7.00, paper.

This book, which was produced by the Small Farm Resources Project of the Center for Rural Affairs in Hartington, Nebraska, should appeal to a wide audience, since it's really two books in one. It is both a handbook of simple economic philosophy and practices that work on family farms, and also a thought-provoking account of a project involving 23 northeastern Nebraska farm families. These farmers are considered by some to be 10 years "behind" their progressive farming neighbors in the Platte River Valley of Nebraska and 20 years behind their counterparts in Illinois. But the project shows that this group of deeply committed family farmers is surviving. With farm foreclosures reaching near-epidemic proportions, their survival may mean they are 10 to 20 years *ahead* of other farmers. That alone makes their philosophy and farming practices worth examining.

Most of the 23 cooperating farms are quite diversified, producing both animals and crops in an area that receives 25 inches of rain yearly. The farmers have a strong ethic regarding resource conservation, a sense of place, commitment to community, and a belief in family farming as a way of life, although they are not a socially cohesive unit like the Amish.

As part of the project, the farmers attended workshops and presentations about resource-conserving alternative practices that emphasized farmers' skills rather than technologies and purchased inputs. The purpose of the project has been to help these farmers not only find, but also test for themselves alternative low-cost farming practices that fit their goals and way of farming. Within the study, goal setting was a priority over solving problems. Making optimal use of farm and family resources took preference over the narrow focus of maximizing production.

The primer is divided into five sections, beginning with a stimulating introduction, "In Search of an Appropriate Alternative Agriculture." It is followed by position papers covering on-farm research, research methodology, alternative farm management practices, and the economic viability of the cooperating farms. A section is devoted to the explanation of sustainable farming concepts, including soil building, alternative crops, small grains, legumes, pastures, biological pest management and weed control. Another section details sustainable farming practices, including composting livestock manure, planting windbreaks, green manures, strip cropping, overseeding of legumes into pastures, brassicas for cool-season grazing, time-controlled grazing, beneficial insects like musk thistle weevils, and alternative crops such as sweet white lupines, triticale, and peas.

What makes these concepts and practices so meaningful is that they were tested in the context of a farming system, rather than in isolation. The farmers involved felt a sense of em

powerment as they tested these principles on their own farms. The study indicates that the farmers and other rural residents felt they were gaining control over their own lives and futures.

As Center staff introduced farmers to alternative farming practices, they stressed two things: the idea that there are approaches to farm management other than those commonly promoted; and the need for farmers to recognize that their farms operate as complex systems made up of many interdependent parts. The families initially tended to be cautious and were not easily convinced of an idea's value. Once convinced, however, they were quite willing to incorporate new ideas into the workings of their farms.

Underlying this focus on appropriate on-farm research is the contention that the practical knowledge, experience and the decision-making skills of the farm population have been vastly underrecognized and underutilized by most of the agricultural research establishment. The research process exposed farm families to a wide range of alternatives they normally would not have heard about. These ranged from some that were outrageous to others that were only slight modifications of current practices.

One alternative was time-controlled grazing. This system was developed by the French scientist Andre Voisin, who found that pasture production could be increased markedly if pastures were divided and animals and grass managed in accordance with sound principles of pasture growth and animal nutrition. This contrasts with most pasture management systems, where the animals are put into the entire pasture for the summer. The pasture appears to fail because of cattle overuse, but it is the management of the pasture which has failed. Therefore, when cooperators were introduced to the idea of time-controlled grazing, several dairy farmers decided to experiment with it. As a result, they now see their pastures as a valuable low-cost resource.

The project strongly emphasized the concept of soil quality, which helped farmers to understand the importance of increasing the organic matter content and water holding capacity of their soil. Teaching them to look at soil in terms of both its chemical composition and its physical and biological characteristics moved them beyond the "N, P, K" school of soil management. Emphasis on soil quality meant closing nutrient loops by using manures and composts wisely, planting cover crops, and using crop rotations, contours and stripcropping where they were appropriate.

Many farmers gained workable ideas from some of the more radical speakers they heard at workshops. But a new idea or technology had to fit or be adaptable to the needs of the farm and the values and goals of the farm family. If it required instead that the farm family adapt to the requirements of the new technology, or forced a significant change in the farm's structure, it usually was rejected. Above all, the farmers focused on a process for establishing priorities, and were geared toward meeting goals rather than merely solving problems. Farmers were encouraged to develop "safety-first" farming as a priority, recognizing that farm income will fluctuate due to weather, prices, and disease. This fluctuation is accepted and expected, and management decisions are made accordingly. Many in agriculture consider this approach to be very conservative.

Center pivot irrigation is an example of a technology that did not fit the farmers' resource-conserving approach to farming. A center pivot irrigation system may reduce the risk of insufficient rainfall, but because its fixed costs are higher, it significantly increases the economic risks from other disasters, such as hail, high winds, extreme heat at pollination, low prices, increasing interest rates or changing federal monetary policy. Once a farm becomes tied to the center pivot irrigation system, it is extremely difficult to move away from it without going bankrupt. The Small Farm Resources Project cooperators preferred to rely on a diverse group of internal and external resources including labor, credit, capital, soil moisture, crop rotations, and livestock, as well as creativity, common sense, family and neighbors. The ideas, philosophies, and processes were probably more important than the actual research activities undertaken as part of the Small Farm Resources Project.

In reporting the experiences of this project, the primer presents individual topics in a straightforward, informative and effective manner. In the chapters on farmers' tests of the various alternative farming practices, the advantages and disadvantages of each method are presented, as well as information on how well they worked. As a researcher, I would have preferred more detail about the methods so that I could have made a clearer evaluation of the results. The figures are out of sequence in the chapter on time-controlled grazing, but can be sorted out with careful reading.

The information in the primer is well presented for pragmatic farmers, especially those in the Midwest, who want to take another look at how they do things. Its straightforward, simple economic philosophy and practices seem to work on actual farms. The narrative style definitely has a point of view, but it is thought-provoking and challenging, and encourages readers to question many standard agricultural assumptions. I would recommend it to county extension people, extension specialists, researchers, and agricultural administrators in addition to farmers. The agricultural establishment would benefit from considering many of the ideas presented here. -- *William Liebhardt, Director, Sustainable Agriculture Program, Cooperative Extension, University of California, Davis, CA.*

Seeds and Sovereignty: The Use and Control of Plant Genetic Resources. 1988. Jack R. Kloppenburg, Jr., Editor. Duke University Press, Durham, North Carolina. 368 pp. $47.50, cloth.

In the past two decades, preservation of the genetic diversity of the world's plants has emerged as a leading international agricultural issue. It also is among the most controversial and

most heatedly debated. Only a small part of the disagreement is scientific. Indeed, the spirit of cooperation among plant breeders from many different countries is very encouraging. The heat comes from the politicizing of the issue into one of "Third World vs. the industrialized world" or "North vs. South" or "developing vs. developed nations." The names by which the regions are called can vary, but the word "versus" is the one usually used to characterize their relationship. The basic conflict involves the disparity between the developing tropics, said to be the source of most of the world's valuable genetic materials, and the industrialized, temperate zone, said to be the main beneficiary.

The narrowest version of the debate focuses on Resolution 8/83 of the U.N.'s Food and Agriculture Organization, adopted in 1983. The main point of the resolution is not at all controversial, and in fact calls for an arrangement that is already widely followed, namely, that "plant genetic resources are a heritage of mankind and consequently should be available without restriction." The problem arises over the additional provision that this principle applies to "special genetic stocks (including elite and current breeders' lines and mutants)." To seed companies in the developed world, this clause strikes at the heart of property rights. To the developing world, it is seen as a way merely to reclaim genetic materials originally taken from them without compensation.

The controversy over this provision was the immediate reason for this book. But even though a wide spectrum of views is represented, none of the authors particularly favors the "special genetic stocks" provision. Several strongly sympathize with the developing world's desire to shift the terms of genetic exchange to even out perceived inequities, but also realize that the proprietary materials included in the resolution would in any case not be particularly valuable to the non-industrialized world. Like the supporters of breeders' proprietary rights, they recognize that the demand for free exchange of privately developed breeding lines is primarily political, a largely symbolic response to economic domination and an attempt to assert countervailing power.

Fortunately, the book covers a much broader range of issues. This makes it far more significant than if it merely dealt with the one proposal that generates the most passion, even if it was not particularly well thought out by those who hoped to benefit from it. The most interesting questions, which are well covered in this book, involve not the disposition of proprietary materials, but rather how to conserve and best utilize traditional cultivated varieties and their wild or weedy relatives. The former are often displaced by modern varieties for which, ironically, they may have provided the essential genetic material; the threat to wild or weedy species comes from the destruction of habitat. Several authors discuss the strengths and weaknesses of various genetic conservation techniques, which include seed banks, restrictions on land clearing in areas naturally rich in genetic resources, fields specifically planted to threatened varieties, and programs to encourage farmers to continue planting traditional varieties. Other important questions taken up in several chapters include the likely value of exotic, unevaluated germplasm compared to materials already used in breeding programs, and the appropriate roles for the various people and institutions involved with plant genetic resources: the international research centers, national seed banks, FAO, private seed companies, and the world's farmers.

The book's 16 chapters fall into two basic types: those that provide background material on these and related questions, and those that advocate particular positions on current policy questions. Among the former are a historical overview of plant genetic resources, by Garrison Wilkes; a discussion of the magnitude and causes of the alarming rate of genetic losses, by Norman Myers; a summary of foreign germplasm's contribution to American agriculture, by Thomas Cox and coauthors; and an explanation of the potential role of new technologies in enhancing germplasm diversity, by Thomas Orton.

The authors that argue particular positions have much to disagree about, despite their general agreement on the "special genetic stocks" question described earlier. Most support the "common heritage" principle and encourage more exchange of genetic material, and many agree that some compensation should be given to the source of that material. However, they differ regarding the best mechanism. Some call for aid to developing countries' plant breeding programs, arguing that it is the lack of programs comparable in quality to those of the developed world, and not the restrictions on proprietary materials, that places the developing world in a subordinate position in exploiting genetic resources. Others propose various forms of monetary compensation, either to the governments of the source countries, or to their farmers. Whether the compensation should be retroactive, and if so, how it should be determined, is another very thorny issue. A notable exception to the general support of the "common heritage" idea is the chapter by the editor, with coauthor Daniel Kleinman. They argue for assertion of national sovereignty over genetic resources as the way the developing world can best exert political and economic leverage in the face of a history of domination by industrialized nations.

The book does an admirable job in covering this complex area in an intelligent and balanced manner. Although the editor has his own strongly-held views, they by no means color the book. In fact, the final chapter, a commentary on the various chapters by the distinguished plant geneticist Jack Harlan, very specifically takes issue with Kloppenburg and Kleinman on the matter of national sovereignty vs. common heritage. A wide range of perspectives is presented, often by very prominent representatives of the major parties involved in the international plant genetics scene. Examples include William Brown, the former head of Pioneer Hi-Bred International, M. S. Swaminathan, director general of the

International Rice Research Institute, and Otto Frankel, who had an important role in several major activities in this area since the 1960s, including chairmanship of FAO's Panel of Experts.

My only criticisms are minor. Occasionally, I felt that some authors were hedging their views on matters of controversy, and were not asserting their positions clearly and forcefully. In a few cases, different authors made directly contradictory statements on a matter where it seemed possible to ascertain the truth. Even if not, the editor might have required the authors to take note of the other view, and either rebut it or seek some middle ground. The most bothersome instance involved the question of how important tropical germplasm is to current breeding programs in temperate, industrialized countries. Everyone agrees that way back, most of our cultivated crops originated in the tropics. However, some say that this means that industrialized agriculture still depends heavily on a continuing flow of genes from the tropics; others say that the dependence substantially ended long ago, and that new genetic materials from the tropics are important only to meet certain highly specialized needs. Finally, a few chapters did not adequately explain some technical concepts in a manner suitable for readers without specialized knowledge of plant genetics.

Regardless of these shortcomings, I can highly recommend this book as a good way for anyone with an interest in agricultural policy to become informed about one of the most pressing policy issues of our times. The book most certainly will be of interest to a far wider audience than just those who are professionally involved in plant breeding or environmental conservation. The issue will not go away soon, and it is hard to think of a more urgent need than to conserve the genetic variety that underlies modern agriculture, to advance the scientific techniques to put it to best use, and to develop appropriate international arrangements that will assure that the results of these techniques will serve the people who are most in need of their benefits. I regard this book as a worthy contribution to the continuing discussions of how to achieve these goals. -- *William Lockeretz, Research Associate Professor, School of Nutrition, Tufts University, Medford, MA.*

Management of Pests and Pesticides: Farmer's Perceptions and Practices. 1987. Joyce Tait and Banpot Napompeth, Editors. Westview Press, Boulder, Colorado. 244 pp. $33.00, paper.

Either national or international pest management practitioners working in developing countries generally consider peasants' knowledge about farming and pests as primitive, inappropriate and outmoded. This perception is derived from the historical development of western science toward specialization rather than holism, and is rooted in the arrogance of some biologists who regard styles of thought based on experience (and not on "scientific experimentation") as non-science. A closer look at farmers' knowledge and perceptions (what ethnoecologists now term ethnoscience) has revealed that local people's knowledge about the environment, vegetation, animals and soils can be very sophisticated.

In many areas, farmers often achieve a richness of knowledge about insects which only would be accessible to Western scientists through a long and expensive research program. In fact, if this knowledge were to be seriously taken into account, substantial time and money could be saved in the development of appropriate pest management technologies. A case in point was the English-sponsored variegated grasshopper control program in southern Nigeria, where farmers' knowledge about the grasshopper's food habits, life cycle, mortality factors, egg-laying behavior, season of attack on cassava, etc. was superior to that of researchers, but was not considered.

Although its title implies that this is what this book is about, with the exception of a few chapters it is not. The book is a collection of papers derived from a conference of the Perception and Management of Pests and Pesticides network (PMPP) that are supposed to be linked to each other through the common premise that understanding farmers' knowledge and attitude to pests and pesticides can be of great value in the development of integrated pest management (IPM) programs. The purpose is to design and implement effective pest control strategies which will be readily acceptable to farmers. The emphasis of the book is on the need to train farmers to recognize pests, diseases, and weeds, so that they can decide for themselves on the need to use or not to use pesticides. Such a naive view ignores the political and economic forces that push farmers in developing countries to use pesticides. Pressure from chemical company salesmen and government extension specialists that embrace the pesticide approach cannot be ignored. Nor can we ignore government subsidies that make pesticides considerably cheaper. Nowhere in the book are guidelines that suggest how farmers and researchers can deal with such pressures.

A few chapters imply that farmers possess a deep knowledge of the biology of pests and that some have developed rational pest management strategies that do not rely on pesticides. The book, however, does not provide a methodology on how to research, improve or preserve such knowledge, or even better, how to integrate it within modern IPM systems. The book implies that modern technology is superior and that the problem is how to disseminate it among farmers. Non-chemical approaches based on local knowledge and local resources are not explored at all, therefore leaving out projects sponsored by non-government organizations in developing countries, who are successfully implementing agricultural technologies tailored to the needs and circumstances of resource-poor farmers. -- *Miguel A. Altieri, Assistant Professor, Division of Biological Control, University of California, Berkeley, CA.*

Abstracted by William Lockeretz

Research reports

An economic analysis of soybean integrated pest management. Catherine R. Greene, Randall A. Kramer, George W. Norton, Edwin G. Rajotte, and Robert M. McPherson. *American Journal of Agricultural Economics* 67(3):567-572 (1985).

This study uses an economic model based on eight years of records from soybean farmers in Virginia who used scouts to recommend whether insecticides should be applied against corn earworm and Mexican bean beetle. The comparison (conventional) treatment was one annual aerial spraying regardless of the actual infestation. Both full-season soybeans and soybeans double cropped with wheat were analyzed. For full-season soybeans, alternatives to scouting for managing the Mexican bean beetle included a trap crop (planting a small portion of the field early, and then spraying it to reduce the beetle population before the rest of the field is susceptible), and release of a parasitic wasp. All treatments were assumed to achieve equal control, with the same resulting yield, so that the only economic difference was in their costs.

All integrated strategies were economically superior to conventional management for both full-season and double cropping. Compared to scouting for the Mexican bean beetle, parasite release was more economical but trap cropping was more expensive. A statistical distribution of weather conditions, yields, and crop prices was used to incorporate risk into the analysis. However, the relative economic attractiveness of the various strategies was unaffected by the weight the farmer gives to risk, i.e., by how much a strategy is downrated because it gives more variable results than another system with the same average returns. The average and the variability of the actual returns under each strategy are not reported. The results are presented only as qualitative comparisons that indicate that even for a farmer who is highly averse to risk, differences in variability were not enough to outweigh differences in average returns.

Effect of tillage system on runoff losses of surface-applied pesticides. T. J. Sauer and T. C. Daniel. *Soil Science Society of America Journal* 51:410-415 (1986).

This study examined loss of pesticides from small plots following application of simulated rainfall. The plots were tilled either conventionally (moldboard plow), or with one of three conservation tillage systems: chisel plow; ridge till; or no-till. Before the experiment, all had been in continuous corn, with residues removed each year. Each tillage treatment received two widely used herbicides, atrazine and alachlor, as well as the insecticide chlorpyrifos (trade name Lorsban). Runoff was sampled twice in each of two consecutive growing seasons: once following a high intensity rainfall simulation in early to mid June, and again following a moderate intensity simulation in late June or mid July. At each sampling period, the investigators measured the concentration of each pesticide in the runoff, the amount of runoff, the concentration in the eroded soil (sediment), and the amount of eroded soil. This permitted determination of both the total loss of pesticide and its distribution between sediment and dissolved phases.

In general, the concentration of pesticides tended to be higher in the conservation systems than under conventional tillage, especially for atrazine. In every case the concentration of chlorpyrifos was well below that of the herbicides, a result which reflects its lower water solubility and greater degree of adsorption on soil. Concentrations of the herbicides were always well below the level considered toxic to pesticide-sensitive aquatic species. However, maximum observed levels of chlorpyrifos, which is much more toxic, exceeded the lethal level for rainbow trout.

The volume of runoff was generally lower with conservation tillage. This offset the higher concentration of pesticide in the runoff, so that there were few differences among the systems with regard to total amount of pesticide lost in runoff. The concentration of atrazine in the sediment was highest in the no-till system, but there were few differences among systems for the sediment concentration of alachlor and chlorpyrifos. Because the no-till and ridge-till system reduced soil loss sharply, the amount of pesticide lost in sediment in these systems was generally lower than with conventional tillage. In general, more chlorpyrifos was transported on the sediment than in the dissolved phase. The opposite was true for the herbicides, reflecting their greater solubility and chlorpyrifos's greater degree of adsorption. Therefore better erosion control with conservation tillage will not by itself control loss of these herbicides.

When losses in both the dissolved and sediment phases were taken into account, total losses of pesticides showed few differences among tillage systems. The exception was that in the year when an intensive rainfall application was made one week after pesticide application, ridge planting had a higher loss of both herbicides than con-

ventional tillage, and no-till had a higher loss of alachlor. This was the only circumstance in which herbicide losses amounted to as much as a few percent of total application (5.8 percent and 5.0 percent for atrazine and alachlor respectively, averaged over all tillage systems). In all other cases, the loss was well below 1 percent, with no substantial differences among tillage systems.

Reviews and analyses

The environmental effects of conventional and organic/biological farming systems. II. Soil ecology, soil fertility, and nutrient cycles. C. Arden-Clarke and R. D. Hodges. *Biological Agriculture and Husbandry* 5(3):223-287 (1988).

This is the second in a series of lengthy review articles, the first of which was abstracted in Volume 2, No. 4, of AJAA. Here the emphasis is on the differing sources of plant nutrients typically used in various farming systems. The three major nutrients (N, P, and K) are given most attention, partly because there has been much more research on them. Although the authors wished to compare organic systems with conventional ones, they point out that most experiments simply compare one form of organic fertilizer (such as farmyard manure) with an inorganic form of the same nutrients. In reality, organic farming differs from conventional practice in many respects, not just in the substitution of one form of fertilizer for another.

Because the comparative environmental effects of conventional and organic systems are so complex, the authors have grouped them into three categories: soil ecology, which covers all organisms other than the crop; soil fertility, or the soil's ability to support the growth of the crop; and nutrient cycles, or the movement of nutrients within the agricultural system and from the agricultural system to the environment. Within each category, effects are further categorized as physical, chemical, and biological. The authors note that this scheme is highly oversimplified, because many effects actually arise from a more complex sequence of interactions.

The following are some of the most important effects reviewed in this article. Use of farmyard manures and rotations of cultivated crops with meadow can increase soil organic matter, while green manures and return of crop residues can at least prevent the decline that would otherwise occur when only inorganic fertilizers are used. An increase in soil organic matter improves the soil's structure, buffering capacity, and cation exchange capacity. Soil organic matter also is generally beneficial in controlling soil-borne plant pathogens, although some harmful effects have been noted. Organic fertilizers often contain minor nutrients that improve nutrient imbalances and make the crop less susceptible to disease; inorganic fertilizers can have the same effect if properly chosen, but the most common macronutrient fertilizers do not contain these minor nutrients. Inorganic fertilizers can also be easily applied in excess, thereby increasing disease susceptibility. Also, the higher ionic concentration that can result from inorganic fertilizer applications can damage crop roots directly.

The improvement in soil structure with organic matter applications permits the crop plants to develop better root systems, and hence facilitates nutrient uptake. In contrast, inorganic fertilizers can have the opposite effect by speeding the breakdown of soil aggregates. Soil organic matter also increases the soil's water holding capacity. Drought resistance is further enhanced because repeated application of organic matter tends to distribute nutrients more uniformly throughout the soil profile and thereby encourages deeper rooting.

Studies of nutrient cycles have mainly dealt with N, since it is most affected by biological/chemical interactions. Under organic fertilization regimes, the increase in the C:N ratio reduces the level of readily available N by immobilizing it in organic form, but the accompanying increase in soil microbial activity leads to a higher rate of mineralization (conversion from organic to inorganic). With inorganic fertilization regimes, the applied N is immediately taken up by the crop, and, therefore, does not increase the level of total soil N. Release of N from organic fertilizers is a slow process, extending its use over several years. Compared to immediately available inorganic N, an organic N source may be better timed to meet the nutrient needs of the crop; it is also less susceptible to leaching.

A more complete comparison of organic and conventional systems must reflect the larger structural features of each, not just the chemical differences between their respective forms of fertilizers. The most important of these is organic farming's preference for mixed farms with cultivated crops and livestock, in contrast to the separation of conventional agriculture into crop farms in some regions and livestock farms in others. This separation discourages return of livestock manures to cropland and prevents the use of rotations of row crops with meadows. Although there are cases of environmental contamination from applications of livestock manures to cropland, such as runoff of P, these result from highly intensive animal units from which the wastes must be disposed. In contrast, on organic farms, stocking rates are moderate and wastes are regarded as a resource to be handled efficiently.

The authors conclude with the overall observation that the conventional approach of providing crop nutrients has been based on an oversimplified model of a barely understood system, and does not take adequate account of the natural processes involved in soil fertility and nutrient cycles. Although this system has been successful in the short term, the accompanying soil degradation could reach the point of irreversible loss of soil fertility. Therefore, fertilization regimes should be designed to enhance biological processes rather than supplanting them with external nutrient supplies.

Farming Alternatives: A Guide to Evaluating the Feasibility of New Farm-Based Enterprises, from Cornell Cooperative Extension, is a workbook designed to help a farm family through a step-by-step analysis of potential new farm businesses. It covers personal and family factors, estimations of available resources, alternative options, market potential, cash flow, and other matters. Exercises include self-tests, checklists, and worksheets. The workbook can be used as a text for workshops, in one-on-one counseling, and as a self-guided analysis, authors say. Although the resources listed at the end of the book are confined to the Northeast, the text itself is more widely useful. The workbook is $5.75 from the Northeast Regional Agricultural Engineering Service, 152 Riley-Robb Hall, Cornell University, Ithaca, NY 14853.

Sustainable Agriculture in Kansas: Case Studies of Five Organic Farms describes the farming techniques of selected Kansas farmers. The analysis includes the financial returns and details the transitions made to non-chemical farming. Overall, the study shows that producers' costs are low and their yields comparable to conventional farmers in the area. Three of the farms rely on livestock; two are cash grain and legume operations. The report is $6 from the Kansas Rural Center, P.O. Box 133, Whiting, KS 66552.

Tax Shelter Surplus and the Tax Reform Act, from the Natural Resources Defense Council, examines tax policies in relation to environmental quality in American agriculture. Areas covered include capital investment, passive loss limitations, deductions, and cash accounting. Overall, the 1986 reforms in the tax code are less likely to stand in the way of an improved rural economy and environment than previous law, the report concludes. Nonetheless, it suggests ideas for further reform. For information, contact the NRDC, 1350 New York Avenue, NW, Suite 300, Washington, DC 20005.

The State of the States: 1988, a report from Renew America, gives a state-by-state analysis of pesticide programs for features ranging from ground water monitoring to farmworker protection. States are ranked for the overall strength of their policies, with California, Massachusetts, and Texas coming out on top. The 50-page report also covers programs in surface water, land use planning, indoor pollution, highway safety, and energy pollution control. It is $15 from Renew America, 1001 Connecticut Avenue, #719, Washington, DC 20036.

Sustainable Agriculture News, in its premier issue from the University of California's Sustainable Agriculture Research and Education Program, describes that program, publications, grants, workshops, and other meetings. Among current events, the editors note the formation of a state-wide cover crop group and a workshop on growing grapes with reduced input. For information, contact the Program at Agronomy Extension, University of California, Davis, CA 95616.

Who Chooses Your Food? A Study of the Effects of Cosmetic Standards on the Quality of Produce, uses oranges and tomatoes as case studies of the relationship between cosmetic food standards and pesticide use. Topics include consumer perceptions, health hazards, and economic effects. Copies are $10 postpaid from California Public Interest Research Group, 1147 South Robertson Boulevard, Suite 203, Los Angeles, CA 90035.

Winning With Water is a detailed description of how to use gypsum blocks to monitor soil moisture for the purpose of reducing irrigation water use. The book reports field studies in the West which show that water use can be reduced by up to 58 percent. The 172-page book is $24.95 plus $2.50 s/h from Inform, 381 Park Avenue South, New York, NY 10016. Inform is a national nonprofit research organization.

Beneath the Wheels of Fortune from the Center for Rural Affairs, is a case study of the economic and environmental impacts of center pivot irrigation in northeastern Nebraska. The development of irrigation led to more specialized and concentrated agriculture dependent on export markets and prone to environmental damage, the report says. Rebuilding a sustainable system will take diversification, crop rotations, field windbreaks, and reversion of marginal lands to dryland farming or pasture, it concludes. The report is $5 plus $1.50 postage from the Center for Rural Affairs, Box 736, Hartington, NE 68739.

April 1988 Conference Report from the Canadian Organic Growers (COG) calls for more coordination between all sectors of the organic food system and for public education on the values of chemical-free foods. A central registry for growers, wholesalers, and retailers is proposed. The 40-page report is $7.50 from COG, c/o Coral MacDonell, Box 1131, Kemptville, Ontario K0G 1J0.

Agriculture Diversification Initiatives: State Government Roles in Rural Revitalization, from the Council of State Governments (CSG), details programs in several states and provides an overview chart of programs in all 50 states. Since 1982, at least 11 states have started special initiatives to help their farmers develop more diversified and economically sound cropping systems, the report says. In Illinois, for example, a state loan program has funded projects including egg-laying facilities, a hydroponic greenhouse, strawberry and turkey farms, and the reopening of a hog-slaughtering plant. The hog plant put 400 rural people back to work, and one of the laying hen projects produced demand for 30,000 tons of feed per year from other farmers. The 16-page bulletin is from the CSG Center for Agriculture & Rural Development, Iron Works Pike, P.O. Box 11910, Lexington, KY 40578

Enhancing Agriculture in Africa, a report from the Congressional Office of Technology Assessment, argues that to keep pace with its population African agriculture will need to double its production in the next few decades. Instead of pointing to a high-input solution, however, it recommends building on existing "low resource" systems used in African farming, herding, and fishing. Systems need to be sustainable within the constraints imposed by poverty, heavy reliance on local resources and family labor, and undependable access to external resources and markets, OTA says. The 330-page report (052-003-01092) is $14 from the U.S. Government Printing Office, Washington, DC 20402. IAA Executive Director Garth Youngberg was an advisor to the study.

Sustainable Agriculture for California: A Guide to Information has been published by the Dry Lands Research Institute at the University of California. The guide lists libraries, ways to access data bases, organizations, directories, periodicals, and books. Copies of the 12-page guide are free while copies last from the Sustainable Agriculture Research and Education Program, U. C. Cooperative Extension, Agronomy Department, Hunt Hall, Davis, CA 95616.

1988 LISA Projects, a 28-page listing of projects funded by the USDA low-input/sustainable agriculture program, gives titles, principal investigators, objectives, and level of support funding for each program. The document is $1 from the Iowa State University Publications Distribution Office, 112 Printing and Pubs Building, Iowa State University, Ames, IA 50011.

Proper Manure Management, a booklet from the University of Delaware, gives an overview of major steps in manure management, including formulas for calculating available nitrogen. It is $2 from the University of Delaware Extension Office, Townsend Hall, Newark, DE 19717-1303.

Proceedings of the On-Farm Composting Conference held at the University of Massachusetts in 1987 includes case studies, presentations on the composting process, economic data, and information on regulations and soil applications. Copies of the 95-page publication are $5 from the Bulletin Distribution Center, Cottage A, Thatcher Way, University of Massachusetts, Amherst, MA 01003.

Pesticide Residues in Food: Technologies for Detection, from the Congressional Office of Technology Assessment (OTA), calls for improved monitoring for pesticide residues in food. Current testing can detect no more than half of the pesticides in use, OTA reports, and does not identify foreign-used pesticides not approved for domestic use. Frequently, it takes more than two days from the time of collecting samples to reporting of results, OTA says. During that time, the food is often sold. OTA suggests improved analytical methods and placing program emphasis on residues with the greatest potential health hazard. The 232-page report (stock #052-003-01132-8) is $10 from the U.S. Government Printing Office, Washington, DC 20402.

Low-Input Farming Systems: Benefits and Barriers, from the House Committee on Government Operations, calls for the federal government to aggressively promote low-input farming. Low-input agricultural practices "hold great promise for preventing ground water contamination and reducing farmers' costs," but the government "must do more to research and promote these technologies," says the report. Adoption of low-input practices is now limited by multiple barriers, the report charges. It cites the limited information available to farmers, mixed signals from USDA about its support for low-input farming, lack of research, and the continued existence of federal commodity and loan programs which discourage adoption of low-input systems.

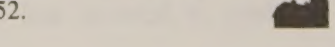
Interagency factors which hinder progress are also targeted for change. Poor coordination between the USDA and the Environmental Protection Agency hinders the EPA in considering nonchemical methods as part of its approach to protecting ground water, the report says. It recommends that EPA's ground water strategy place more emphasis on these alternatives. USDA should request increased funding for its low-input program to ensure effective information transfer to farmers, and Congress should work to eliminate legal barriers to low-input farming when it reauthorizes the farm bill in 1990, the report says.

Low-Input Farming Systems: Benefits and Barriers, (House Report 100-1097) is available from the Environmental, Energy and Natural Resources Subcommittee, Room B-371 B&C, Rayburn House Office Building, Washington, DC 20515.

The Southwest Wisconsin Farmers' Research Network 1986-87 (June, 1988), from the Wisconsin Rural Development Center (WRDC), summarizes success factors in its two-year program of on-farm research. Research topics should be chosen by farmers who form a network for the initiative, the report says. A coordinator is essential and cooperation with research specialists and extension agents improves both on-farm and related university research. In 1988 nine farmers are participating in trials, and farmer-members have developed statewide and national recognition for their work. Copies of the report are $3 from the WRDC, P.O. Box 504, Black Earth, WI 53515.

Organic and Low-Spray Fruit Production Conference Proceedings, from the January, 1987, meeting at Cornell University, includes biology and management information and marketing ideas from scientists, extension personnel, organic fruit growers, and processors. The 131-page notebook is $10 from the Natural Organic Farmers' Association, P.O. Box 454, Ithaca, NY 14851.

Sowing a Future for the Land, from the Land Stewardship Project, reports on a three-year program to organize land and water stewardship activities in Winona County, Iowa. Action included organizing 975 school children to plant 20,000 trees, neighborhood meetings, and negotiating with absentee landowners. Copies are $5 from the LSP, 180 East Main Street, Lewiston, MN 55952.



International conference explores sustainable farming systems

About 450 people met for five days in September in Columbus, Ohio, for the International Conference on Sustainable Agricultural Systems, the largest such event ever held under the auspices of land grant universities. The conference organizers, scientists from the state universities of Ohio, North Carolina, and Pennsylvania, included several American co-organizers of a similar conference held in Padua, Italy, in April, 1988 (see the Special Report in Volume 2, No. 4 of this journal). Although the audience was mainly from the U.S., some 20 other countries were also represented. IAA personnel featured prominently as presenters, session chairmen, and coauthors: Executive Director Garth Youngberg; IAA board members James Lukens, Katherine Clancy, and Warren Sahs; AJAA staff members William Lockeretz and James Parr; and AJAA editorial board members Miguel Altieri, David Bezdicek, Frederick Buttel, Charles Francis, Stephen Gliessman, Richard Harwood, Larry King, and Patrick Madden.

The conference comprised three types of activities: two and a half days of invited papers in plenary sessions; a half day of parallel workshops along with a follow-up panel discussion; and two evenings of poster presentations. Participants also visited the Ohio State Farm Science Review, where they could examine a few exhibits on sustainable agriculture among acres of sprayers, four-wheel drive tractors, and eight-row corn combines.

The opening session presented six overviews of broad conceptual questions and policy issues in sustainable agriculture. Speakers at this session were from a range of public and private institutions, including Winrock International, USDA, USAID, World Bank, Institute for Alternative Agriculture, National Academy of Sciences, and Rodale Institute (all of whom, except for IAA and NAS, were also conference sponsors).

Many of these speakers began by discussing the most fundamental question of all: What do we mean by "sustainable agriculture?" This question came up many times throughout the conference, but no clear answer was apparent. Some speakers emphasized resource and environmental considerations, while others attached great importance to social and economic equity issues as well.

The remaining plenary sessions dealt mainly with the ecological and technological aspects of sustainable agriculture, including plant nutrients, crop rotations, pest problems, soil conservation, and livestock management. These papers were mainly from land grant universities, and most were oriented towards the U.S. situation. However, one session was devoted to sustainable agriculture in the tropics, and included speakers from South America, Africa, and Asia. In this session and in later discussions, several people noted the fundamental differences underlying sustainable agriculture in developed and developing countries.

Only a few invited papers dealt with economic, social and political questions, but these were the main concern of the parallel workshop sessions. Here, participants offered opinions on five aspects of sustainable agriculture: government policies; technical assistance for the developing world; research, education, and extension strategies; the agrochemical industry; and farmer participation in research. An added discussion session organized by some participants dealt with the role of women in sustainable agriculture. The main points covered in these workshops were discussed further by the full audience.

The conference also included about 75 poster presentations covering a substantially broader range of approaches and topics than the formal sessions. Some reported new research results from investigations in soil science, entomology, sociology, economics and agroecology among other fields. A second type described the programs of public and private research institutions and grass-root organizations. Still others presented more abstract discussions of conceptual issues in sustainable agriculture.

Although the formal program did not emphasize any specific activity in sustainable agriculture, one that came up repeatedly in both the papers and the discussions was USDA's research and education program on low-input agriculture. This program allocates the $3.5 million appropriated in 1988 under the Agriculture Productivity Act. Talks were given by both Paul O'Connell, Deputy Administrator of the Cooperative State Research Service, which is in charge of the program, and Patrick Madden, Program Manager for CSRS. The program uses the acronym LISA (for "Low-Input/Sustainable Agriculture") as the official designation of the approach it hopes to foster. While acknowledging the convenience of a single term that everyone can use, some conference participants appeared doubtful about the particular choice.

The size of the audience clearly indicated that sustainable agriculture is attracting ever-increasing attention. More significant than sheer numbers, however, were the affiliations of the audience and the speakers, many of whom came from research institutions and administrative agencies without a long record of involvement in the subject. As noted by several participants who worked on sustainable agricultural issues in relative isolation in past years, it will be interesting to see how the field develops now that it has been embraced by the agricultural mainstream and has been given a place on the established agenda.

Guide for authors

AJAA will publish original research on biological, physical, social science aspects of alternative agriculture. We particularly welcome multi-disciplinary studies, but papers from specific discipline also are invited. However, since AJAA readership is much broader than for a single-discipline journal, highly specialized terminology should be explained or avoided. The significance of a statement, or the reasoning behind a conclusion, may have to be spelled out more than in a more specialized journal. Research papers usually should be no longer than about 20 double-spaced pages.

Nomenclature and technical details

Research papers should use the International (SI, or metric) system throughout. Write out "liters". "Metric ton", although not strictly an accepted SI unit, can be used for data referring to "ordinary life," such as national crop output, as opposed to experimental data. Occasional use of common unit equivalents in parentheses is permitted, mainly for relatively exotic SI units.

The binominal or trinominal designation of a plant or animal species, and the cultivar where relevant, should be given in parentheses the first time the common name of the species is mentioned. Either name may be used thereafter. The same applies to names of chemicals that have both a common name and a chemical name. Do not use brand names except where the chemical is produced under a unique brand name. In those cases the brand name, identified as such, may be given the first time the chemical is mentioned. Nutrient applications should be given in elemental form (N,P,K). Oxide forms can be used in describing commercial fertilizers.

Title page

The title page should give the following information (all flush left): 1) title of the paper; 2) names of authors; 3) affiliation and office address of authors, and 4) acknowledgements, if any. See examples in this issue of AJAA.

Abstract

The abstract should be 200 to 400 words suitable for readers from a broad range of disciplines. It should avoid highly-specialized terminology that might be appropriate for a single discipline journal. Take particular care that the significance of the work is made clear, even to readers from a different field.

Reference list

References should be listed in alphabetical order by author's name, and by year for a particular author (with letters after the year if needed). If a sole author is also the lead author of papers with multiple authors, use the following order: single author (by year); two authors (alphabetically by second author's name); three or more authors (by year). Repeat the author's name for each reference. Use initials only for first and middle names. Give the names of all authors in the reference; never use "et al."

Use full names of journals, institutions, conferences, etc., except for extremely familiar abbreviations like "Dept." Remember that an abbreviation familiar to you may not be familiar to readers outside your field. If in doubt, write it out.

The reference list uses no quotation marks, italics, boldface, or underlining. Only the names of books and periodicals are in initial capitals. Names of papers, book chapters, pamphlets, and bulletins are not capitalized. Page numbers are written out in full (e.g., 1108-1123, not 1108-23). The volume is given if page numbers begin at 1 for each issue.

Citing references

Cite references in the text by last name and year, with chapter or page numbers if the reference is a book or lengthy report. For two authors, give both names. Do not use "et al." unless there are at least three authors.

Footnotes

AJAA does not use bibliographic or substantive footnotes. All bibliographic references should be at the end of the text. Instead of substantive footnotes, include the material in the main text or consider eliminating it.

Manuscript preparation

The entire manuscript, including abstract and references, should be typed on one side of standard-size paper, double spaced, with margins of at least one inch all around. Starting with the title page, label all pages in the upper righthand corner with the lead author's last name and the page number. Do not use hyphens unless the hyphen is part of the word. Do not underline anything except species names.

Follow the section headings style used in this AJAA issue. All headings are flush left, with no underlining or italics.

Tables should fit on one page, be numbered consecutively with Arabic numerals, and be on a separate sheet. Leave extra space to separate columns. Every figure and table should be mentioned at least once in the text.

Submission of manuscripts

Submit four high-quality copies to Editor, American Journal of Alternative Agriculture, Suite 117, 9200 Edmonston Road, Greenbelt, MD 20770. The cover letter should state that the manuscript is an original contribution that has not been published elsewhere in substantially the same form; that it is not currently under consideration elsewhere, and that permission has been obtained for any copyrighted material used.

How you can help support the scientific and educational needs of a sustainable agricultural system

A growing number of Americans have become concerned about the long-term sustainability of our food production system. Farmers and agricultural scientists are among those raising questions about the growing dependence of modern farming on nonrenewable resources, the depletion of our resource base through soil erosion, and heavy reliance on chemical fertilizers and pesticides. Continued heavy reliance on farm chemicals is questioned because they have become an expensive production input. Their widespread use also raises questions about human and animal health, food quality and safety, environmental quality, and the continued demise of the family farm.

Low-input alternative farming methods address these economic and environmental challenges. Alternative production systems point the way toward more profits, more individual choice, and long-term sustainability for our food system. More must be done to develop effective ways to make sure research, education, and information sources are readily available to farmers who want to adopt these techniques.

The Institute for Alternative Agriculture needs your help in meeting this challenge. We are a nonprofit tax-exempt research and education organization set up in 1983 to encourage and facilitate the adoption of low cost, resource conserving, and environmentally sound farming methods. We work directly with government agencies, colleges and universities, producer groups, and other institutions that provide research, education and information services to farmers.

The Institute also provides these services:

- *A resource to lawmakers and others who influence agricultural research, education, and information policy*
- *A voice for alternative agriculture in Washington*
- *A sponsor of research and education outreach programs*
- *A national clearinghouse for information on alternative agriculture*
- *A publisher of reliable scientific information on agricultural sustainability*

If you're interested in helping us, please contact our office at 9200 Edmonston Road, Greenbelt, MD 20770. The phone number is (301) 441-8777.

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